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A Globally Efficient Means of Distributing UTC Time & Frequency Through GPS

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Abstract

Time and frequency outputs comparable in quality to the best laboratories have been demonstrated on an integrated system suitable for field application on a global basis. The system measures the time difference between 1 pulse–per–second (pps) signals derived from local primary frequency standards and from a multi–channel GPS C/A receiver. The measured data is processed through optimal SA Filter algorithms that enhance both the stability and accuracy of GPS timing signals.

Experiments were run simultaneously at four different sites. Even with large distances between sites, the overall results show a high degree of cross–correlation of the SA noise. With sufficiently long simultaneous measurement sequences, the data shows that determination of the difference in local frequency from an accepted remote standard to better than 1×10^{-14} is possible. This method yields frequency accuracy, stability, and timing stability comparable to that obtained with more conventional common–view experiments. In addition, this approach provides UTC(USNO MC) in real time to an accuracy better than 20 ns without the problems normally associated with conventional common–view techniques.

An experimental tracking loop was also set up to demonstrate the use of enhanced GPS for dissemination of UTC(USNO MC) over a wide geographic area. Properly disciplining a cesium standard with a multi–channel GPS receiver, with additional input from USNO, has been found to permit maintaining a timing precision of better than 10 ns between Palo Alto, CA and Washington, DC.

Introduction

Because GPS provides time traceable to Coordinated Universal Time (UTC), and its rate is syntonized with the international definition of the second, it provides a world–wide resource for time and frequency with heretofore unprecedented accuracies and precisions.

Although selective availability (SA) limits navigation and position accuracy to slightly better than the 100 meter specification, a method of filtering the SA noise has been developed for timing during the past year. This method provides enhanced GPS (EGPS) operation[1].. The EGPS approach has been shown to provide a real–time UTC(USNO MC) with stabilities of a few nanoseconds and frequency stabilities of 1×10^{-14}. The EGPS timing technique is a systems approach. The quality of the output will depend on the clock used with the receiver.

An EGPS clock based on a high quality quartz oscillator has demonstrated timing stabilities of 20 ns rms, long-term frequency stability of better than 1×10^{-13}, and elimination of frequency drift and reduction of environmental effects on the system output[1].

GPS timing is becoming extremely important to society and to science. Major users include the Bureau International des Poids et Mesures (BIPM), which provides the standard for time and frequency, UTC; 45 national timing centers; NASA JPL's Deep Space Network; the world-wide measurement of the rapid-spin rates of the millisecond pulsars; NIST's global time service; NASA's timing of space platforms; and numerous other calibration and timing laboratories.

Of the six different methods of using GPS for timing[2], three are the most popular. These are GPS direct, EGPS, and GPS Common-View. Of these, EGPS has by far the best performance/cost ratio.

GPS common-view requires that the clock sites participating use single satellites according to a pre-arranged schedule and exchange data. A different approach (EGPS) will yield essentially the same data almost in real-time, but with a simplified procedure. A multi-channel GPS receiver approach permits looking at all satellites in view. Even at continental distances, common satellites are viewed most of the time. Thus, a high degree of correlation can be expected, even with sites on opposite sides of a continent. Rather than using a single satellite for a relatively short period of time and sharing raw data to determine frequency and time changes, EPGS uses proper processing of data from all available satellites to obtain time comparison between the local site and UTC(USNO MC), as broadcast by GPS. The frequency of the remote clock can be compared directly with the broadcast value of UTC(USNO MC) or with similar data received directly from USNO. These comparisons have accuracy uncertainties of 10^{-14}, or less than 10^{-14}, respectively.

Long integration times require the use of clocks that exhibit sufficient long-term stability to maintain stable time and frequency. Presently, commercially available primary cesium-beam frequency standards exhibit typical accuracy of $\approx 2 \times 10^{-13}$, long-term stability (better than 1×10^{-14} beyond 1 week), with minimal environmental sensitivity.[3] A feature of these standards is that they operate as steerable clocks. The output time and frequency can be controlled by known amounts so that they agree with an external reference. These clocks may be ensembled together to improve robustness of the system.[4] The ensemble output can be shown to be better than the best physical clock in the system. Reliability is enhanced since the system continues uninterrupted with only some loss in performance should any one of the clocks fail.

Timing signals are now available from the full GPS constellation of 24 or more satellites offering world-wide, multiple satellite timing information referenced to UTC(USNO MC) with a high level of redundancy, reliability, and robustness. In addition, low-cost commercial multi-channel GPS C/A receivers with 1 pps outputs are available.

SA Filtering

Until now, a significant problem with using GPS has been the imposition of Selective Availability (SA). SA is an intentional modulation added to the satellite clock signal such that a non-secure receiver cannot achieve full dynamic position accuracy. The recent development of effective,

optimal, SA filtering techniques based on the spectral characteristics of SA permits receiving UTC(USNO MC) time as broadcast by GPS almost as if SA were not present.[5]

These techniques provide no assistance in determining dynamic positioning, but are a major enhancement in determining time and frequency. Since UTC(USNO MC) is currently steered to UTC within ±60 ns, and the broadcast correction from GPS has a documented accuracy of about ±20 ns with respect to UTC(USNO MC), the system described provides a real–time access to UTC. Accurate measured values of the time difference between UTC (via GPS) and UTC(USNO MC) are available after a 48 hour delay. These can be used to improve further the timing accuracy to better than 10 ns.

Experimental Results: Part I

During April and May 1994, time difference data were taken at four sites. These were: the US Naval Observatory (USNO), Washington, DC, the National Institute of Standards and Technology (NIST), Boulder, CO, Hewlett–Packard Laboratories (HPL), Palo Alto, CA, and the Hewlett–Packard Santa Clara Division (SCD), Santa Clara, CA.

At each site, the same, low–cost commercially available, 6–channel GPS C/A timing receiver was installed. The time difference between the 1 pps signal derived from the GPS receiver and the 1 pps from the local primary frequency standard was measured using conventional time–interval measurement techniques. Used in this experiment were: the Master Clock at USNO, the output from Microstepper B (tied to UTC(NIST) at NIST, a single HP5071A cesium–beam frequency standard at HPL, and an active ensemble of three HP5071A standards at SCD.

No attempt was made to synchronize the GPS 1 pps signals to the local signals. The receiver time delays were not calibrated, but as all receivers were identical, a reasonable assumption is that the delays were approximately the same. Finally, except for USNO, no attempt was made to correct for all of the known fixed time delays either in the GPS antenna or in the 1 pps delay from the local standard. As a result, the data obtained can be used to determine frequency accuracy, frequency stability, time stability, but not time accuracy between the various sites.

The experimental results are shown in Figures 1 through 4. Each plot presents 300 second averaged data for each data point, since 300 seconds was the shortest common measurement time of the four sites involved. At three of the sites, data points were taken every second, then 100 consecutive values were averaged and the 1 second data discarded. At the fourth site, 1 second data points were averaged every 60 seconds. Also shown as a white line in each plot are the SA filtered data, obtained by post–processing the original experimental data with the SA filter algorithm. The mean value has been subtracted from all data in the plots. The SA filter algorithm used was such that in an on–line system, the same outputs could be obtained in real time.

The filtered data in Figure 1 was compared with the output of a secure two–frequency keyed GPS receiver. This receiver used the measured rather than the broadcast value for the ionospheric delay correction. The rms of the time difference between the filtered estimate and the secure receiver was 1.5 ns.

The improvement in time–domain stability obtained through the use of this optimum filtering routine is shown in Figure 5. The upper line shows the modified Allan Deviation (MDEV) of the NIST time difference data before filtering. The data are dominated by SA noise, and the slope is about -3/2, indicating a white–phase noise process. The lower line is the MDEV of the filtered NIST data. The amplitude of the noise has been reduced to approximately the noise level expected of a cesium standard. At 200,000 seconds, outside the stop–band of the SA filter, the value of MDEV observed is of the same order as the noise of the UTC–corrected GPS. The improved time domain stability is obtained at the cost of a longer response time.

Table 1 presents some of the experimental results obtained after all data have been corrected for constant frequency offsets and slopes. The correction factors are shown. Significant is an almost 500–fold improvement in time–domain stability at 300 seconds and the uniformity from site to site.

A close examination of the data in Figures 3 and 4 (HPL and SCD) indicates a high degree of correlation. Given that the two sites are less than 25 km apart, this is not unexpected since both sites see the same GPS satellites at essentially the same time. A difference plot of the data is shown in Figure 6. As the data for the four sites share a common binning scheme, the cross–correlation coefficients were calculated for several selected pairs over the period of common data bins between the sites. The results are shown in Table 2. As expected, correlation decreases with distance between observation sites. This is undoubtedly due to differences in the tropospheric and ionospheric correction factors and a decreasing number of satellites common to both sites.

Experimental Results: Part II

An experimental GPS tracking loop was set up to demonstrate the use of EGPS for dissemination of UTC(USNO MC) at a slightly improved accuracy over that from Part I. The experiment consisted of steering a cesium clock at Hewlett–Packard Laboratories in Palo Alto CA using the output of a multi–channel GPS receiver. The effects of the GPS–to–UTC(USNO MC) time–difference, and un–modelled receiver delays were minimized by using the readings from an identical receiver at USNO in Washington, DC the output of which was compared with the USNO master clock.

In order to avoid uncertainties due to the broadcast GPS to UTC(USNO MC) corrections, which could be as large as 100 ns, both receivers operated in the "GPS" timing mode.

At USNO the 1 pps output of a 6–channel receiver in the "position–hold mode" was timed with reference to UTC(USNO MC). Average time differences were computed using data extending over two days, evenly weighted. The averages were assigned to the modified Julian date (MJD) corresponding to the center of gravity of the data, and placed in a computer data file which could be read by ftp over Internet. The data file was automatically copied daily by the computer at HPL that managed the tracking loop. On receipt, the data in the file was usually between one and two days old.

At HPL the 1 pps output of an identical receiver in the same operating mode was compared with the 1 pps output of an HP 5071A cesium standard. Each hour, the readings taken in the

preceding 60 minutes were averaged and placed in a data file. A second–order feedback loop was used to steer the cesium standard. The inputs to the feedback calculation were the averaged time difference between the local clock and the output of the GPS receiver, and the averaged, delayed, data from USNO. The USNO data was processed by a simple predictor to estimate the current value of the GPS–UTC(USNO MC) time–difference. This value was subtracted from the local time difference and used to calculate a proportional frequency correction for the cesium standard.

The USNO data was subtracted from corresponding 2–day averages of the local time differences and summed into an integral that was scaled to give the frequency correction for the cesium standard. Effectively, over 90% of the 1 pps pulses at each site were used in the algorithm in order to minimize SA and quantization noise in the receiver. A block diagram of the tracking system is shown in Figure 7.

Initial operation of the tracking loop extended over 40 days. No independent check on the system accuracy with comparable resolution was available, so the results were analyzed on the basis of self–consistency. Figure 8 shows a histogram of the local two–day time differences, with the USNO two–day averages subtracted. The distribution is acceptable, with an rms value of 4 ns. This data shows the tracking error and is not affected by noise at frequencies lower than the loop cut–off, or noise that is coherent at both locations. This noise level compares quite well with the estimate of the cesium standard noise given by $\tau * \sigma_y(\tau)$ calculated for 2 days, which is 3.5 ns. The noise in the tracking loop is shown in Figure 9, which shows the Allan deviation calculated for the frequency corrections applied each 6 hours to the cesium standard. The deviations are compatible with the noise expected from the cesium standard, when the loop transfer function is taken into account. At 4 days the Allan deviation of the frequency corrections is 1.5×10^{-14}. This represents the rms total of the cesium standard noise and the noise introduced by the GPS tracking loop including SA.

This performance suggests that excellent results can be obtained with time–tracking loops using multi–channel GPS receivers, even in the presence of SA. For good time resolution, a high quality local clock is essential. The performance of the loop described could be improved by better algorithms for estimating the real–time GPS–UTC(USNO MC) difference, and for minimizing diurnal effects in the GPS data. The performance of this loop will also depend on the dynamics and magnitude of the GPS–UTC(USNO MC) time difference, which was comparatively small during this experiment.

Summary

The full set of data indicates that the EGPS technique permits a stable local clock to be steered accurately to UTC(USNO MC) using the GPS timing signal. The experimental results indicate that over a one month time period, frequency transfer accuracies of a few $\times 10^{-15}$ are possible. Although no attempt was made to correct for fixed time delays in these experiments, it appears that sufficient accuracy can be obtained to maintain a local time scale close to the performance limits of the GPS system if the system delays are carefully determined.

Acknowledgments

The authors sincerely acknowledge the active assistance of personnel from the United States Naval Observatory, and Victor Zhang and Marc Weiss of the Time and Frequency Division of the National Institute of Standards and Technology.

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[3] J.L. Johnson and J.A. Kusters, *"A New Cesium Beam Frequency Standard — Performance Data,"* Proceedings of the 1992 IEEE Frequency Control Symposium, IEEE Catalog No. 92CH3083-3, pp. 143–150, June 1992

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[5] D.W. Allan and W.P. Dewey, *"Time-Domain Spectrum of GPS SA,"* Proceedings of the ION GPS-93, Sixth International Technical Meeting of the Satellite Division of the Institute of Navigation.

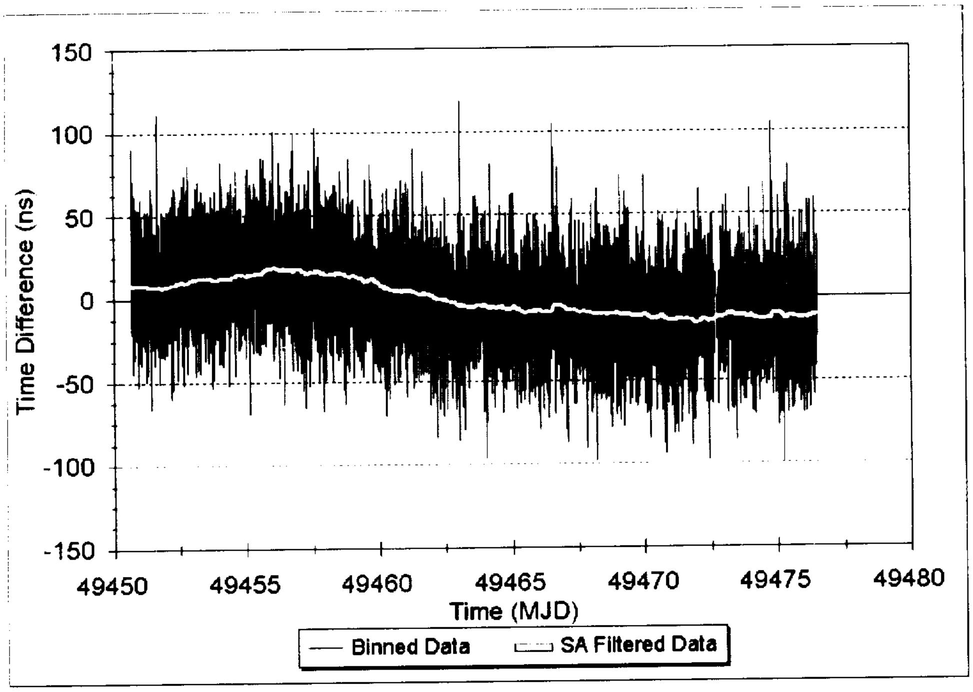


Figure 1. GPS vs. USNO Master Clock -- 300 second binned data

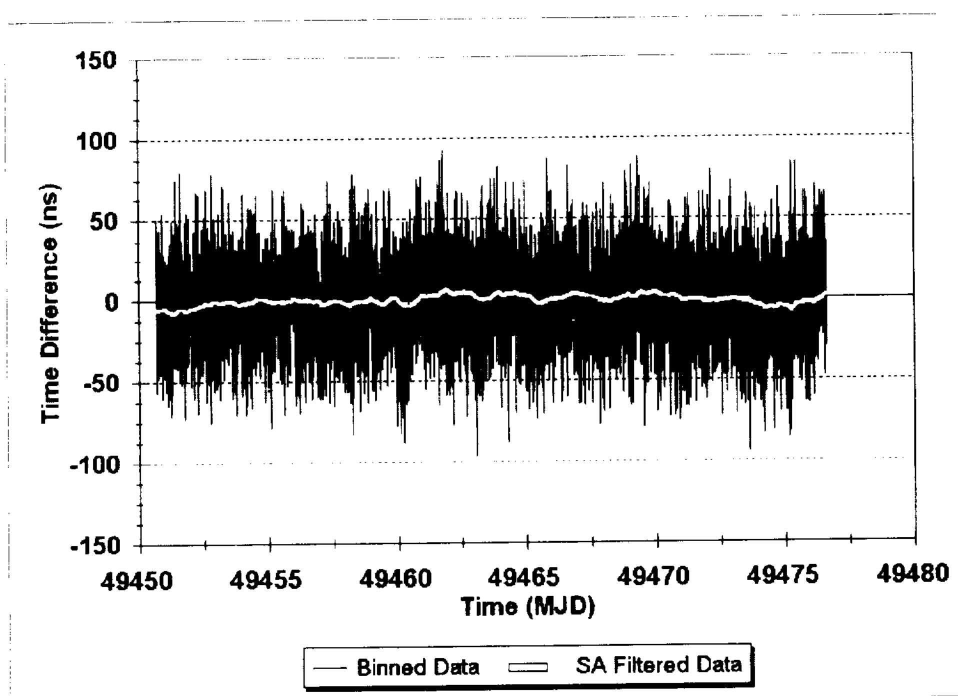


Figure 2. GPS vs. NIST Microstepper B -- 300 second binned data corrected for offset and slope.

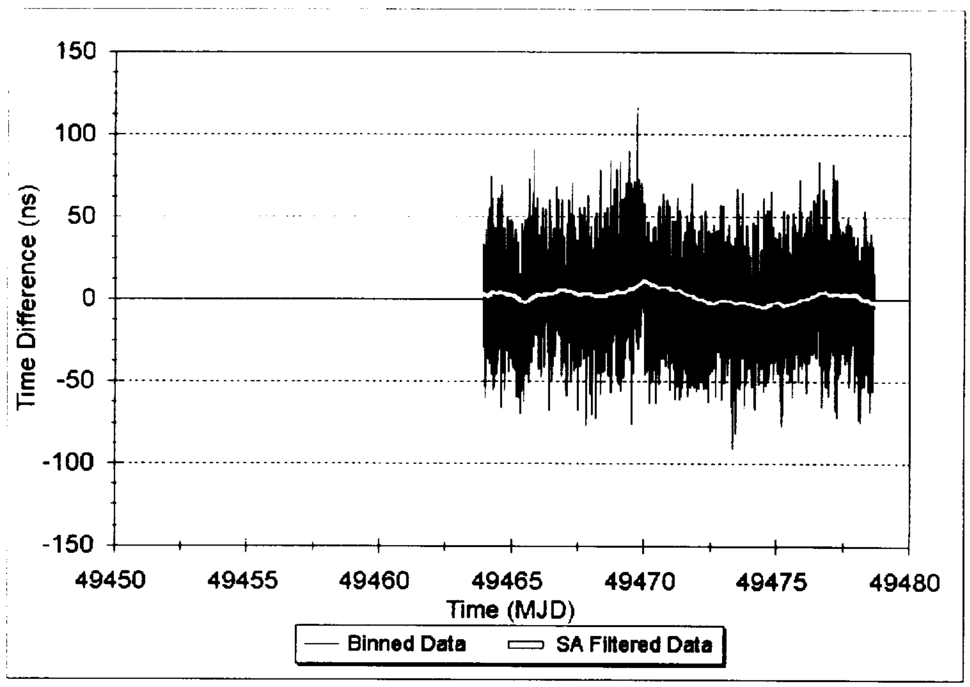


Figure 3. GPS vs. HPL HP5071A -- 300 second binned data

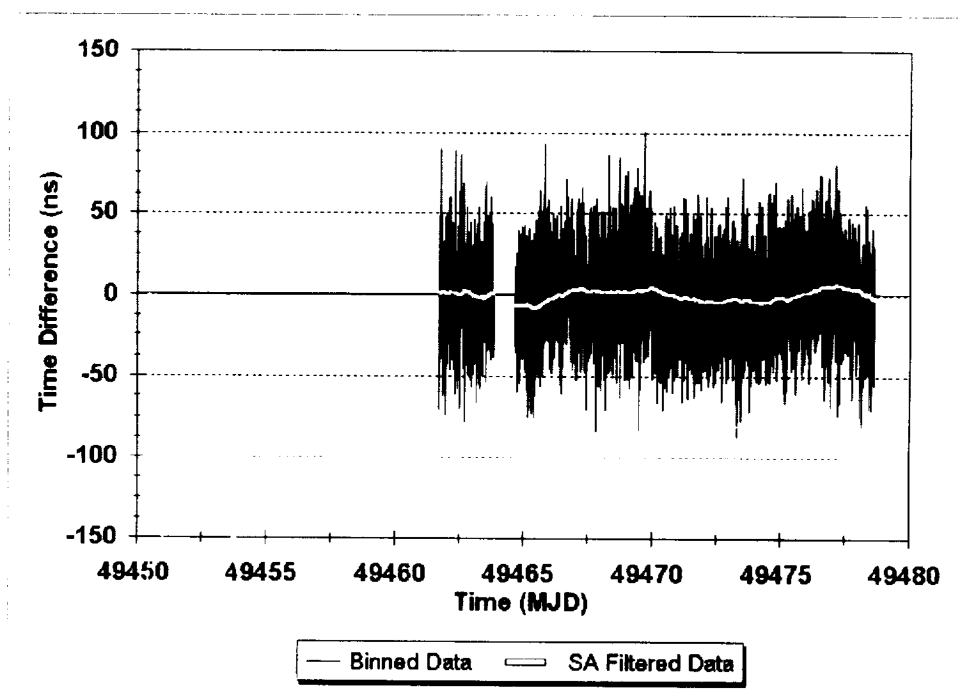


Figure 4. GPS vs SCD HP5071A Ensemble -- 300 second binned data corrected for offset and slope

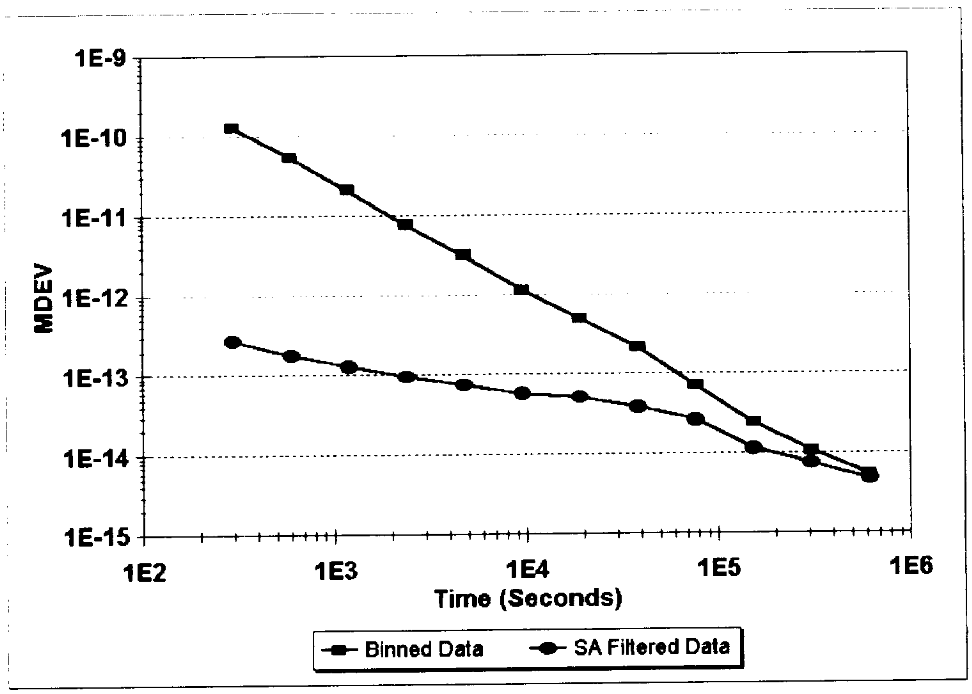


Figure 5. Modified Allan Variance, NIST Data

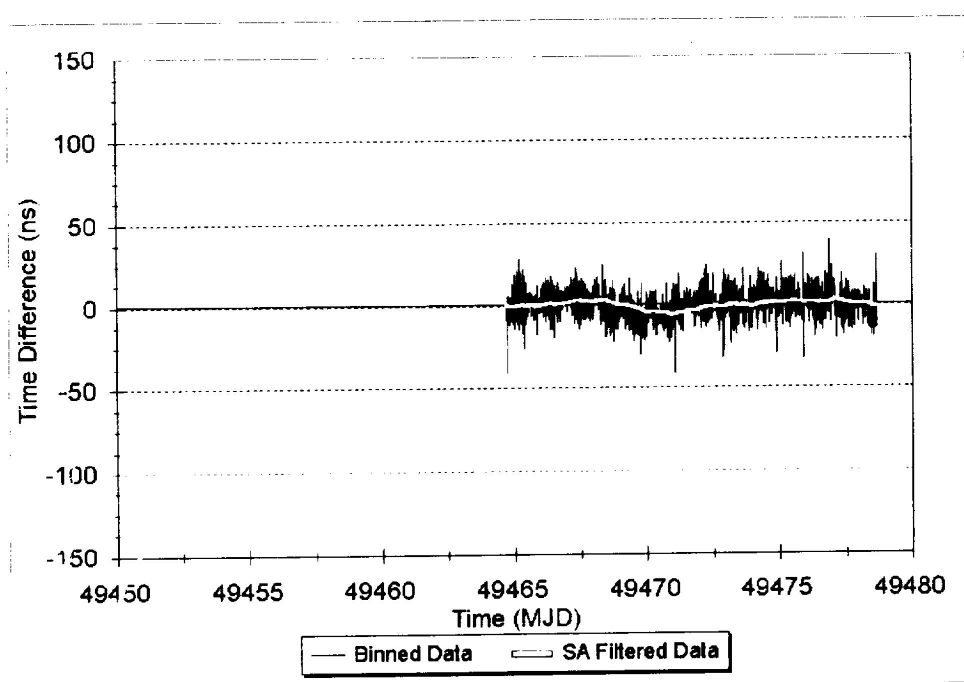


Figure 6. Difference data, SCD - HPL

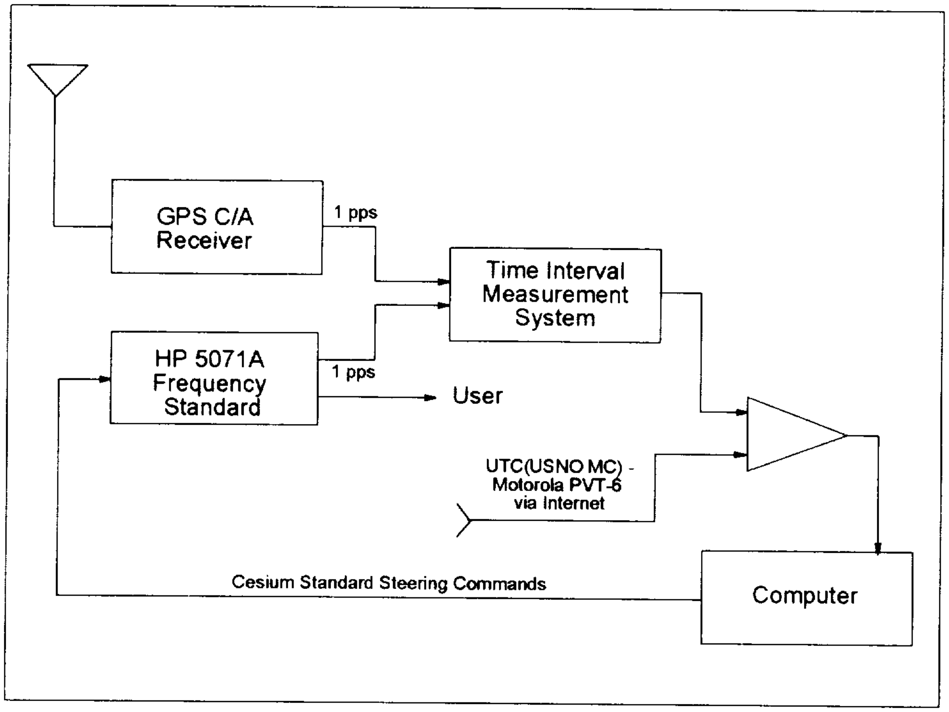


Figure 7. Block Diagram, GPS Disciplined Cesium Standard

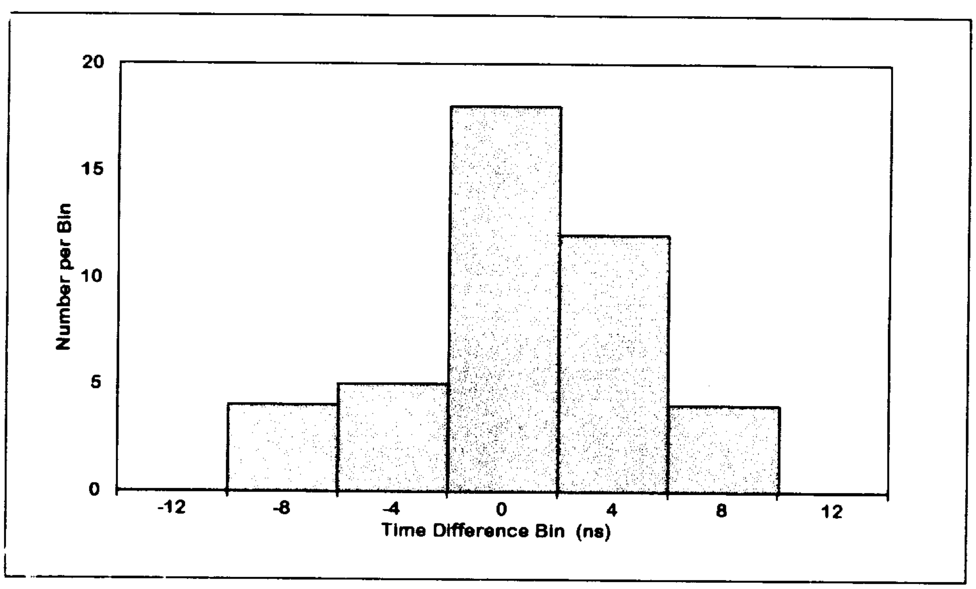


Figure 8. Histogram, HP5071A Disciplined to UTC(UISNO MC) Local Two-day Time Differences,

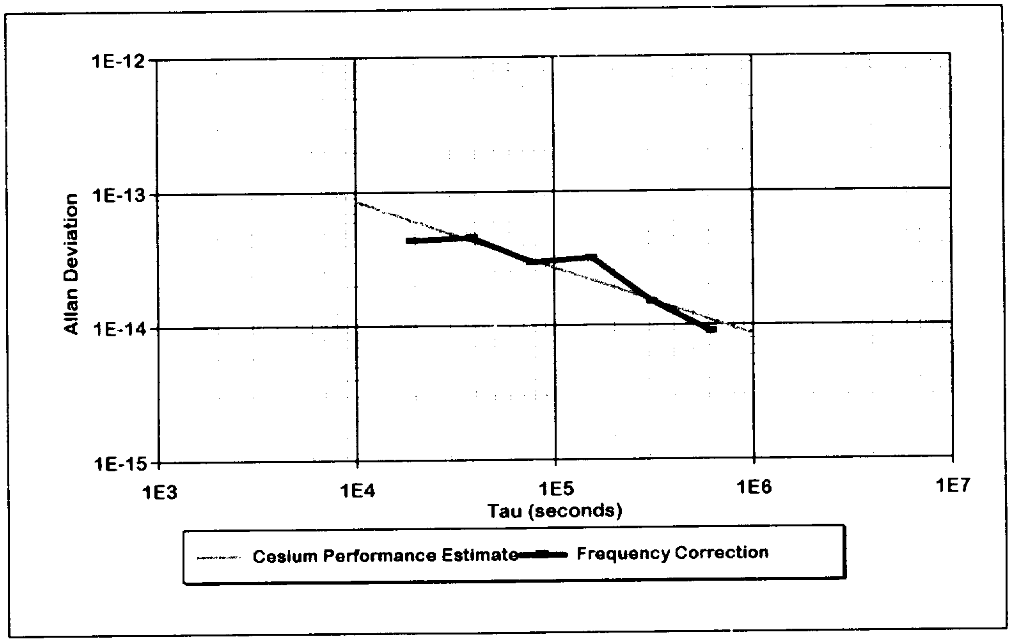


Figure 9. Allan Deviation, HP5071A Disciplined to UTC(USNO MC), steering data

	USNO	NIST	SCD	HPL
Offset (ns)		1146	579	571
Rate (ns/day)		1.8	8.9	-0.3
$\sigma_y(\tau=300$ sec) - original data	1.30×10^{-10}	1.28×10^{-10}	1.26×10^{-10}	1.26×10^{-10}
$\sigma_y(\tau=300$ sec) - filtered data	2.71×10^{-13}	2.69×10^{-13}	2.63×10^{-13}	2.63×10^{-13}

Table 1. Experimental Results, Part I

USNO -- NIST	0.67
NIST -- SCD	0.76
SCD -- HPL	0.96

Table 2. Normalized Cross-correlation Coefficients, Part I

TUTORIAL PTTI MEASUREMENT TECHNOLOGY

CHAIRMAN: DR. FRED L. WALLS, NATIONAL INSTITUTE FOR STANDARDS AND TECHNOLOGY

This workshop is divided into three parts. The first part teaches the fundamentals and the basics of AM and PM noise measurements. The second part uses this background in the basic measurements to develop error models for PM and AM measurements. These models are then illustrated by selected practical examples. The emphasis is on identifying parameters to monitor and pitfalls to avoid. A few examples of PM and/or AM noise in selected components are presented. Fractional frequency stability in the time domain is easily calculated from phase noise measurements. This approach is particularly powerful for short measurement times or when there are significant spurious signals.

The third part details some approaches to the measurement problems that extend the frequency range and improve the accuracy and/or speed of the measurements.

I. FUNDAMENTAL CONCEPTS AND DEFINITIONS IN PM AND AM NOISE METROLOGY

Eva Pikal
NIST/University of Colorado

A. Fundamental concepts
B. Simple PM noise measurement systems
C. Simple AM noise measurement systems

II. DISCUSSION OF ERROR MODELS FOR PM AND AM NOISE MEASUREMENTS

Fred L. Walls
NIST

A. Error model for PM noise measurements
B. Error model for AM noise measurements
C. PM and AM noise models
D. Conversion of PM data to $\sigma_y(\tau)$ and mod$\sigma_y(\tau)$

III. STATE-OF-THE-ART MEASUREMENT TECHNIQUES FOR PM AND AM NOISE

Craig W. Nelson
SpectraDynamics

A. Ultra wideband measurements ($f = 0.1$ Hz to 1 GHz)
B. Integral AM and PM noise standards
C. Ultra low-noise PM and AM measurement systems $S(f) \leq -190$ dBc/Hz)

FUNDAMENTAL CONCEPTS AND DEFINITIONS IN PM AND AM NOISE METROLOGY

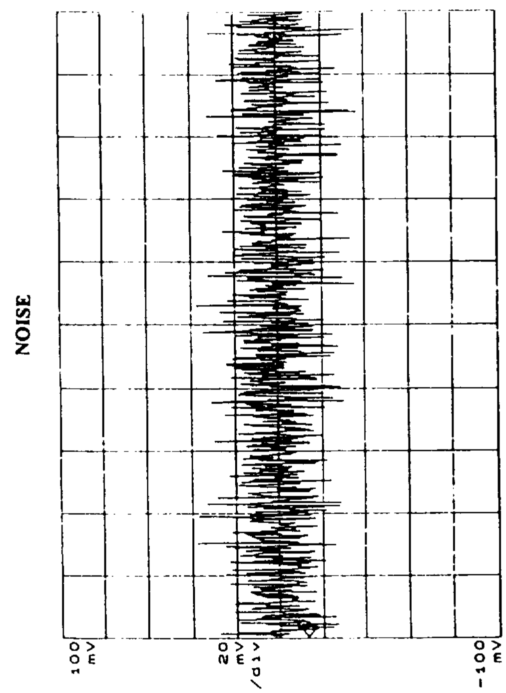
Eva F. Pikal
NIST/University of Colorado

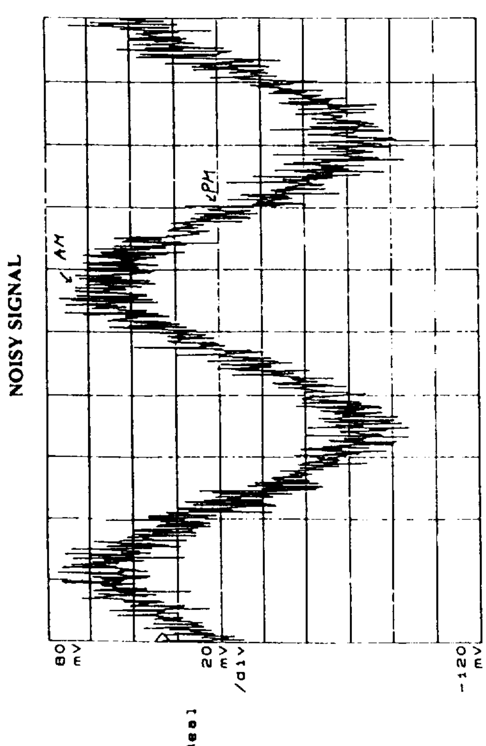
FUNDAMENTAL CONCEPTS

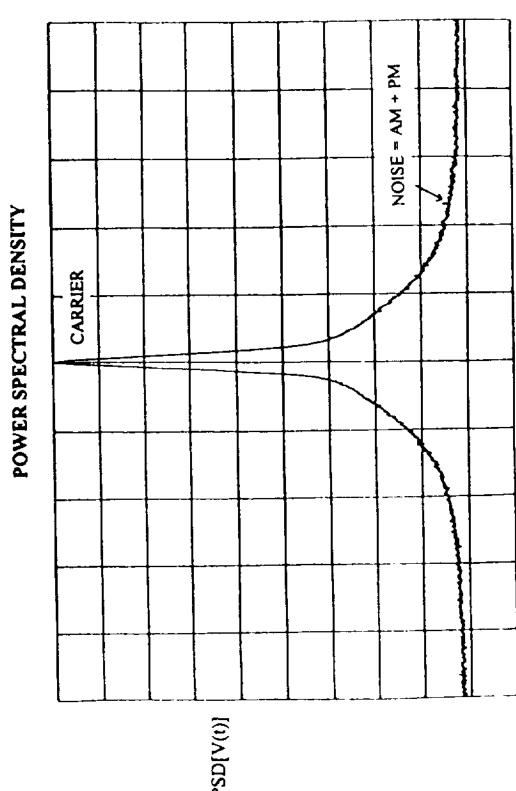
SIMPLE PM NOISE MEASUREMENT SYSTEMS

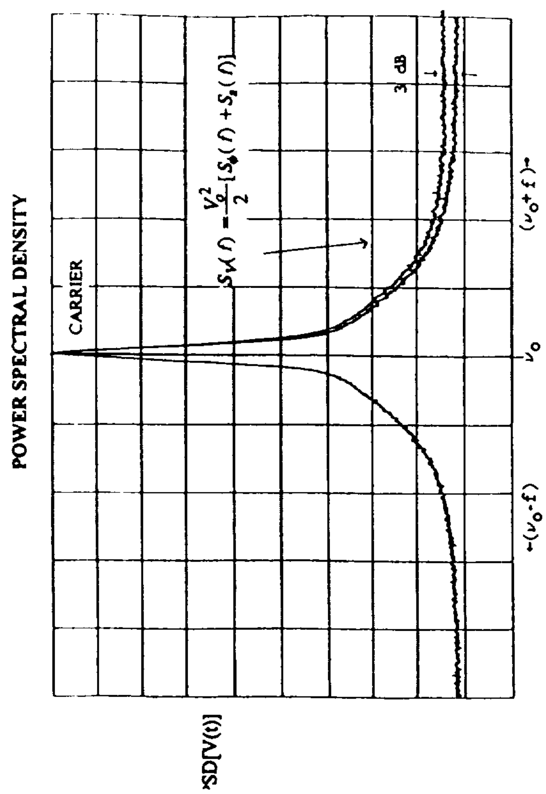
- TWO OSCILLATOR METHOD
- DELAY LINE
- CAVITY DISCRIMINATOR

SIMPLE AM NOISE MEASUREMENT SYSTEMS

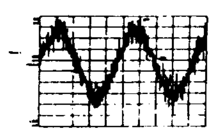








PHASE AND AMPLITUDE FLUCTUATIONS



$$V(t) = [V_o + \varepsilon(t)]\cos(2\pi\nu_o t + \phi(t))$$
$$phase = 2\pi\nu_o t + \phi(t)$$

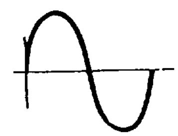
$$\omega(t) = \frac{d}{dt}[phase]$$
$$\nu(t) = \frac{1}{2\pi}\frac{d}{dt}[2\pi\nu_o t + \phi(t)]$$
$$\nu(t) = \nu_o + \frac{1}{2\pi}\frac{d}{dt}\phi(t)$$

Fractional frequency deviation

$$y(t) = \frac{\nu(t) - \nu_o}{\nu_o} = \frac{1}{2\pi\nu_o}\frac{d}{dt}\phi(t)$$

WAVE THEORY REVIEW

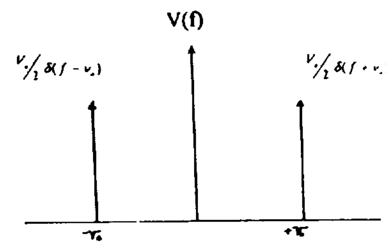
perfect signal



$$V(t) = V_o\cos(2\pi\nu_o t)$$
$$phase = 2\pi\nu_o t$$

$$T = period = 1/\nu_o$$

Fourier Transform:



PHASE/AMPLITUDE NOISE RELATIONSHIPS

$$S_\phi(f) = [\Delta\phi(f)]^2\frac{1}{BW} \quad 0 < f < \infty \quad [\frac{rad^2}{Hz}]$$

$$S_a(f) = \frac{[\Delta\varepsilon(f)]^2}{V_o^2}\frac{1}{BW} \quad 0 < f < \infty \quad [\frac{1}{Hz}]$$

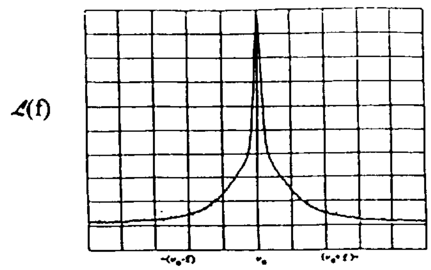
$$y(t) = \frac{1}{2\pi\nu_o}\frac{d}{dt}\phi(t)$$

derivative in time = multiplication by ω in freq
= multiplication by ω^2 in spectral density

$$S_y(f) = \frac{1}{[2\pi\nu_o]^2}(2\pi f)^2 S_\phi(f)$$

$$S_\phi(f) = [\frac{\nu_o}{f}]^2 S_y(f) \quad 0 < f < \infty$$

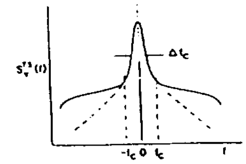
$$S_\phi(f) = \mathcal{L}(\nu_o - f) + \mathcal{L}(\nu_o + f)$$



$$\mathcal{L}(f) = \frac{1}{2} S_\phi(f)$$

$$dBc/Hz = 10\log(\mathcal{L}(f))$$

POWER SPECTRAL DENSITY OF A NOISY SIGNAL



Double side-band spectral density:

$$S_V(f) \cong \frac{V_o^2}{2}[e^{-I(f_c)}\delta(f) + \quad S_\phi(f) + S_a(f)]$$

$$0 \le f \le \infty$$

$$I(f) = \int_{f_c}^{\infty} S_\phi(f)df$$

I(f) = integrated phase modulation due to pedestal

$\delta(f)$ = carrier with frequency $\pm f_c$

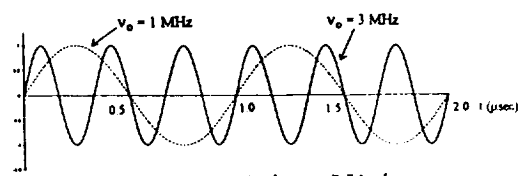
Power in carrier = $\frac{V_o^2}{2}e^{-I(f_c)} \approx \frac{V_o^2}{2}$ for $I(f_c) << 1$

RMS PHASE DEVIATION

$$\varphi^2(f)_{BW} = \int_{f-BW/2}^{f+BW/2} S_\varphi(f)df \ rad^2$$

FREQUENCY MULTIPLICATION/DIVISION EFFECTS ON PM NOISE

Frequency Multiplication



$$\nu_{o2} = N\nu_{o1} \qquad \Delta\phi_2 = N\Delta\phi_1$$

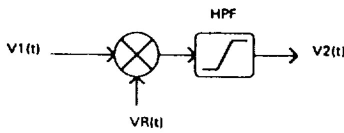
$$S_{\phi_2}(f) = \frac{[\Delta\phi_2]^2}{BW} = \frac{N^2\Delta\phi_1}{BW} = N^2 S_{\phi_1}(f)$$

FREQUENCY DIVISION:

$$\nu_{o2} = \frac{\nu_{o1}}{N}$$

$$S_{\phi_2}(f) = \frac{S_{\phi_1}(f)}{N^2}$$

FREQUENCY TRANSLATION



$$S_\phi(f,\nu_2) = S_\phi(f,\nu_1) + S_\phi(f,\nu_R) + S_{\phi T}(f)$$

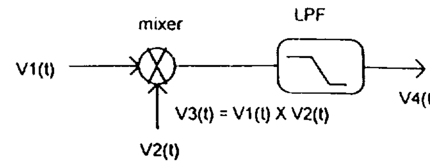
WHERE $\nu_2 = \nu_1 + \nu_R$

$S_\phi(f,\nu_R)$ = PM NOISE OF REFERENCE SIGNAL

$S_{\phi T}(f)$ = PM NOISE ADDED BY THE TRANSLATOR

$S_\phi(f,\nu_2)$ DEPENDS ON THE DETAILS OF THE TRANSLATION

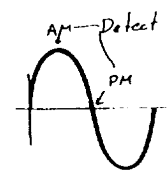
BASIC CONFIGURATIONS OF NOISE MEASUREMENTS



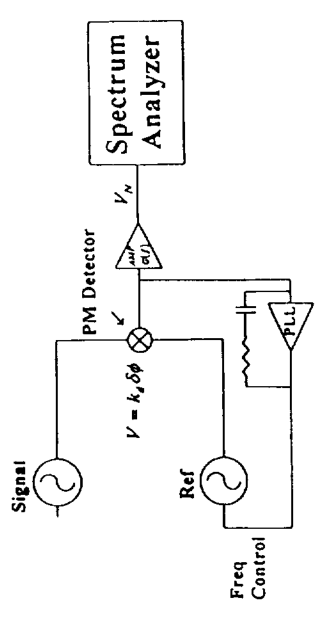
$$V_1(t) = [V_1 + \varepsilon_1(t)]\cos[2\pi\nu_o t + \phi_1]$$
$$V_2(t) = [V_2 + \varepsilon_2(t)]\cos[2\pi\nu_o t + \phi_2]$$

$$V_3(t) = \frac{A_1A_2}{2}\{\cos[2\pi(2\nu_o)t + \phi_1 + \phi_2] + \cos[\phi_1 - \phi_2]\}$$

$$V_4(t) = \frac{A_1A_2}{2}[\cos(\phi_1 - \phi_2)]$$
$$AM \Rightarrow \phi_1 - \phi_2 = \pi n$$
$$PM \Rightarrow \phi_1 - \phi_2 = \frac{\pi}{2} + \pi n$$



Simple PM Measurements



$\frac{PSDV_N}{[k_d G(f)]^2}$ measures $S_\phi(f)$ of the Signal plus the system noise.

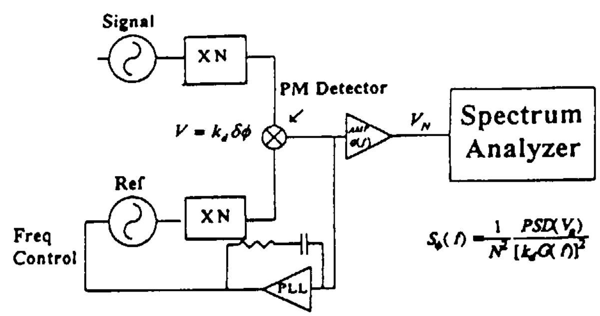
It is difficult to seperate the system noise from a signal with low PM noise. Results uncorrected for PLL and gain variations with Fourier frequency.

NOISE TERMS INCLUDED IN $\frac{PSD(V_n)}{K_d^2 G(f)^2}$

$$S_\phi(f) = \frac{[\Delta\phi_A(f) - \Delta\phi_B(f)]^2}{BW} + \frac{V_n(f)^2_{mixer}}{K_d^2 BW} + \frac{V_n(f)^2_{amp}}{K_d^2 BW}$$
$$+ \frac{V_n(f)^2_{SA}}{K_d^2 G(f)^2 BW} + S_{aA}(f)\beta_A^2 + S_{aB}(f)\beta_B^2$$

$$S_\phi(f)_{pair} = S_{\phi A}(f) + S_{\phi B}(f) + \frac{V_n(f)^2_{system}}{K_d^2 BW} + S_{aA}(f)\beta_A^2 + S_{aB}(f)\beta_B^2$$

NOISE FLOOR IMPROVEMENT USING FREQUENCY MULTIPLIERS



$$S_\phi(f) = \frac{1}{N^2}\frac{PSD(V_N)}{[k_d G(f)]^2}$$

TO GET NOISE FLOOR SET A = B

$$S_\phi(f)_{Noise\ Floor} = (2\pi f \tau_{delay})^2 S_{\phi A}(f) + \frac{V_n(f)^2_{system}}{K_d^2 BW} + S_{aA}(f)\beta_A^2 + S_\phi(f)_{power\ splitter}$$

$$\tau_{delay} = \frac{n\pi}{2}\frac{1}{\upsilon_o}$$

TO CALCULATE INDIVIDUAL PM NOISE FOR AN OSCILLATOR

$$S_\phi(f)_{AB} + S_\phi(f)_{AC} - S_\phi(f)_{BC} = 2S_{\phi A}(f) + \frac{V_n^2}{K_d^2 BW} + 2S_{aA}(f)\beta_A^2$$

DISCUSSION OF DIRECT PHASE COMPARISON

ADVANTAGES

HIGHEST RESOLUTION (LOWEST NOISE FLOOR)

NOISE FLOOR MEASURED WITH INFERIOR OSCILLATOR

VERY WIDE BAND PERFORMANCE

INEXPENSIVE

DISADVANTAGES

REQUIRES A REFERENCE OF COMPARABLE STABILITY

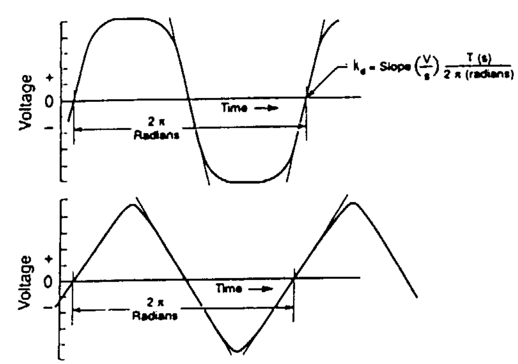
REQUIRES PHASE-LOCKED-LOOP (PLL) TO MAINTAIN $\delta\phi < 0.1$ rad

CALIBRATION DIFFICULT FOR $f \ll$ PLL BW

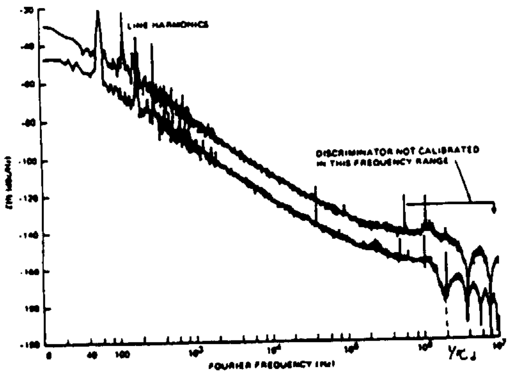
SENSITIVE TO HARMONIC DISTORTION

FREQUENCY RESPONSE DEPENDS ON POWER & LOAD

CALIBRATION FACTOR k_d



DETERMINATION OF τ_d

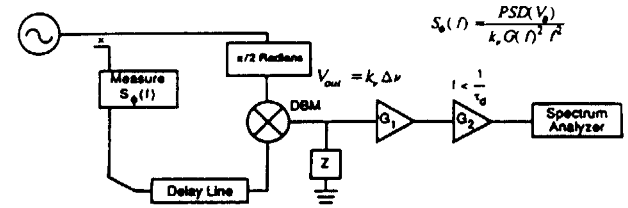


From Infrared and Millimeter Waves, Vol 11, pp 239-289, 1984 (also in NIST Technical Note 1337)

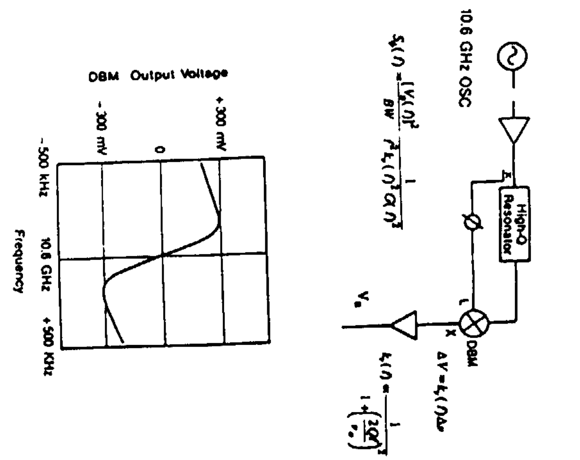
MEASUREMENT OF $S_\phi(f)$ USING A DELAY LINE

$$S_\phi(f) = \frac{\nu_0^2}{f^2} S_y(f)$$

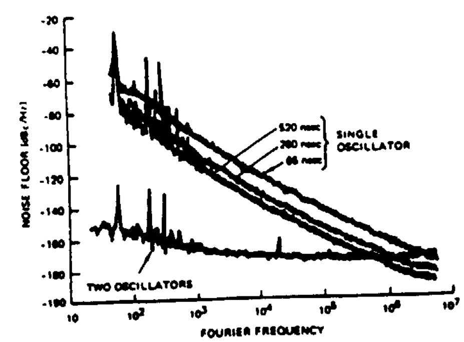
$$S_\phi(f) = \frac{PSD(V_0)}{k_\nu G(f)^2 f^2}$$



MEASUREMENT OF PHASE NOISE USING A HIGH-Q CAVITY

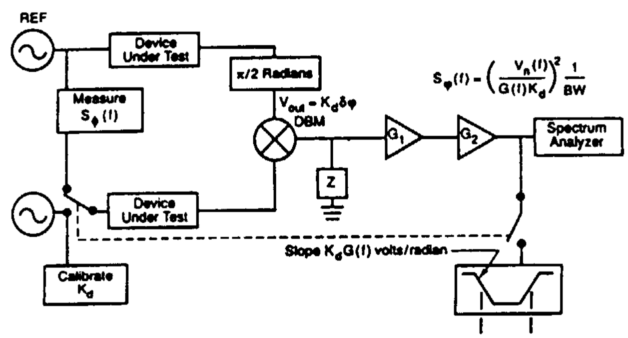


NOISE FLOOR COMPARISON FOR TWO MEASUREMENT SYSTEMS: DELAY LINE SYSTEM VS. TWO OSCILLATOR SYSTEM



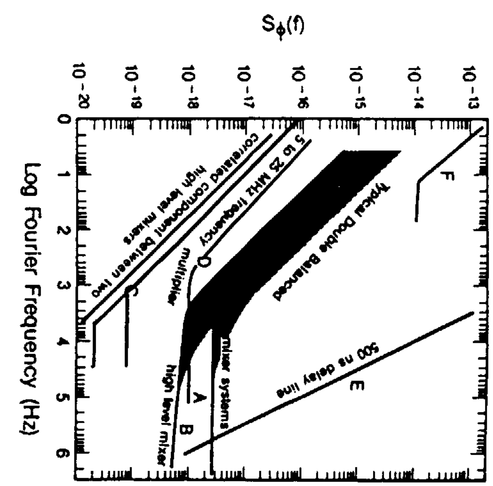
From: Infrared and Millimeter Waves, Vol. 11, pp. 239-289, 1984 (also in NIST Technical Note 1337).

Measurement of $S_\varphi(f)$ for Two Amplifiers



DIRECT FREQUENCY COMPARISONS	DIRECT PHASE COMPARISONS
ADVANTAGES:	
DOES NOT REQUIRE SECOND SOURCE	LOWEST NOISE FLOOR
SYSTEM TRACKS FREQUENCY CHANGES IN SOURCE	NOISE FLOOR MEASURED WITH INFERIOR OSCILLATOR
NO PLL EFFECTS	VERY WIDE BAND PERFORMANCE
SIMPLE CALIBRATION $V = G\,k\,\Delta\upsilon$	INEXPENSIVE
DISADVANTAGES:	
NOISE FLOOR SCALES AS $1/f2$ NEAR CARRIER	REFERENCE OF COMPARABLE STABILITY
NOISE FLOOR DIFFICULT TO MEASURE	REQUIRES PLL TO MANTAIN $\Delta\phi < 0.1$ rad
DIFF. CAVITIES REQUIRED FOR EACH υ	CALIBRATION DIFFICULT FOR $f <<$ PLL BW
DIFF. CAVITIES/DELAY LINES FOR DIFF. f	SENSITIVE TO HARMONIC DISTORTION
DIFFICULT TO MEASURE BEYOND CAVITY BW OR BEYOND DELAY LINE TIME	FREQUENCY RESPONSE DEPENDS ON POWER & LOAD

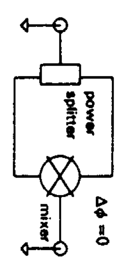
Comparison of Noise Floor for Different Techniques



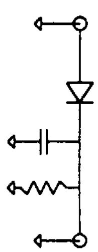
AM NOISE DEFINITION

$$S_a(f) = \left(\frac{\Delta\varepsilon}{V_o}\right)^2 \frac{1}{BW}$$

AM DETECTORS

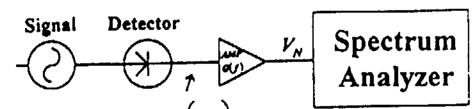


Mixer Detector



Diode Detector

Simple AM Measurement



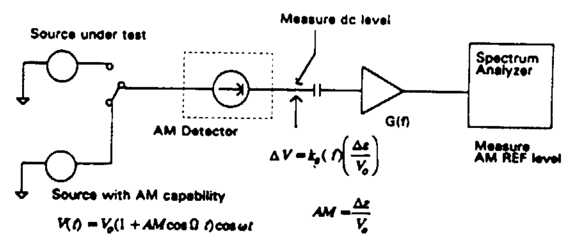
$$V(t) = k_e \delta\left(\frac{\varepsilon}{V_0}\right)$$

$$PSD(V_N) = \frac{V_N(f)^2}{BW} = [k_e(f)G(f)]^2 \left(\frac{\Delta\varepsilon}{V_0}\right)^2 \frac{1}{BW}$$

$\frac{PSD V_N}{[k_e G(f)]^2}$ **measures $S_e(f)$ of the Signal plus the system noise.**

It is difficult to seperate the system noise from a signal with low AM noise.

Determination of $[k_a(f)G(f)]$ for AM Measurement Systems



AM at the input signal: $\frac{1}{2}\left(\frac{\% AM}{100}\right)^2$ AM at output: AM REF level

$$[k_e(f)G(f)]^2 = \frac{\text{AM at Output}}{\text{AM at Input}} = \frac{(AM\ REF\ \text{level})^2}{\frac{1}{2}\left(\frac{\% AM}{100}\right)^2}$$

Fundamental Concepts and Definitions in PM and AM Noise Metrology

TUTORIAL – QUESTIONS AND ANSWERS

Note from the editor

The questions were asked at various points during the presentation. They were transcribed and are presented here at the end of each tutorial.

JIM COMPARO (AEROSPACE CORP.): So S_v is the power spectrum density of that full voltage signal?

EVA PIKAL (NIST): Yes.

JIM COMPARO (AEROSPACE CORP.): And the first you said was what?

EVA PIKAL (NIST): The carrier.

JIM COMPARO (AEROSPACE CORP.): I see three terms there. One is contribution due to the phase noise; one is a contribution to the amplitude noise; and then there's a term out in front. And what is that?

EVA PIKAL (NIST): That's just a carrier, right? That's – you know, if it were ideal, it would just be a delta function at the frequency of oscillation.

JIM COMPARO (AEROSPACE CORP.): I guess my question is – and maybe I'm getting way ahead, but if there is some correlation between the amplitude noise and the phase noise, then the power spectrum of the voltage wouldn't necessarily be symmetric, would it? And so would it be fair to sort of consider these things as folded over on top of one another?

EVA PIKAL (NIST): I believe this assumes there is a correlation between AM noise and PM noise in the signal.

MARC A. WEISS (NIST): I am looking at "requires a reference of comparable stability." I thought you said we could use the oscillator under test as a reference as well.

EVA PIKAL (NIST): That's to measure the noise floor. You need a different reference to measure phase noise of the test oscillator. You need another oscillator. To measure the noise floor, you need to use the single oscillator to get rid of the noise of the source and the reference.

II. DISCUSSION OF ERROR MODELS FOR PM AND AM NOISE MEASUREMENTS

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walls@bldrdoc gov-Internet

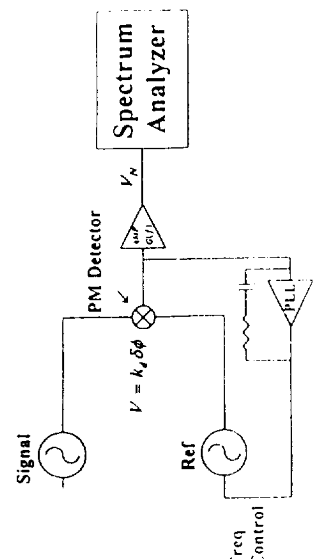
A. Error model for PM noise measurements

B. Error model for AM noise measurements

C. PM and AM noise models

D. Conversion of PM data to $\sigma_y(\tau)$ and mod$\sigma_y(\tau)$

Simple PM Measurements



$\frac{PSDV_N}{[k_d G(f)]^2}$ measures $S_\phi(f)$ of the Signal plus the system noise.

It is difficult to seperate the system noise from a signal with low PM noise. Results uncorrected for PLL and gain variations with Fourier frequency.

ERROR MODEL FOR PM MEASUREMENTS

1 DETERMINATION OF K

2 DETERMINATION OF AMPLIFIER G(f)

3 PLL EFFECTS (IF ANY)

4 CONTRIBUTION OF AM NOISE

5 HARMONIC DISTORTION

6 CONTRIBUTION OF SYSTEM NOISE FLOOR

7 CONTRIBUTION OF REFERENCE NOISE

8 STATISTICAL CONFIDENCE OF DATA

9 LINEARITY OF SPECTRUM ANALYZERS

10 ACCURACY OF PSD FUNCTION

1. DETERMINATION OF K

TRANSDUCER SENSITIVITY DEPENDS ON

A. Frequency

B. Signal power and impedance, reference power and impedance

C. Mixer termination at all three ports

D. Cable lengths

ACCURACY OF DETERMINATION DEPENDS ON DEGREE ABOVE PARAMETERS HELD CONSTANT PLUS

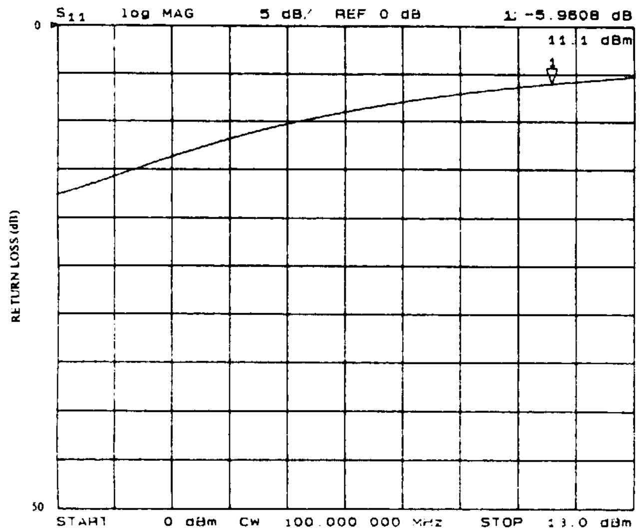
A. Symmetry of waveform

B. Signal-to-noise-ratio

C. Phase deviation from 90°-depends on noise level, dc offset-may depend on f

CALIBRATION CONDITION MUST REPLICATE THE MEASUREMENT CONDITION AS CLOSELY AS POSSIBLE

[illegible]
A LO OF 15 dBm



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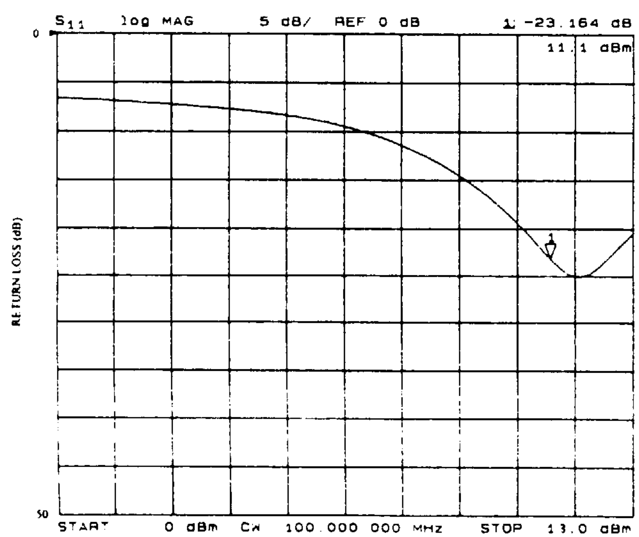
MIXER B RETURN LOSS VERSUS RF POWER AT 100 MHZ AND
A LO OF 15 dBm



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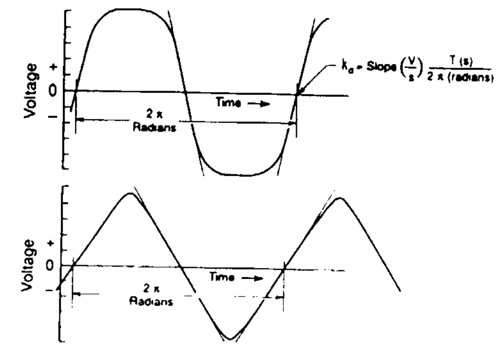
MIXER OUTPUT VOLTAGE VERSUS PHASE (TIME)



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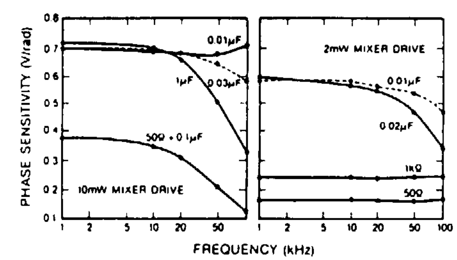
MIXER SENSITIVITY Kd VERSUS IF LOAD



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2. DETERMINATION OF AMPLIFIER GAIN VERSUS FOURIER OFFSET

G(f) DEPENDS ON

A Intrinsic amplifier G(f)

B Mixer output impedance

C Signal power, impedance, and cable length through B

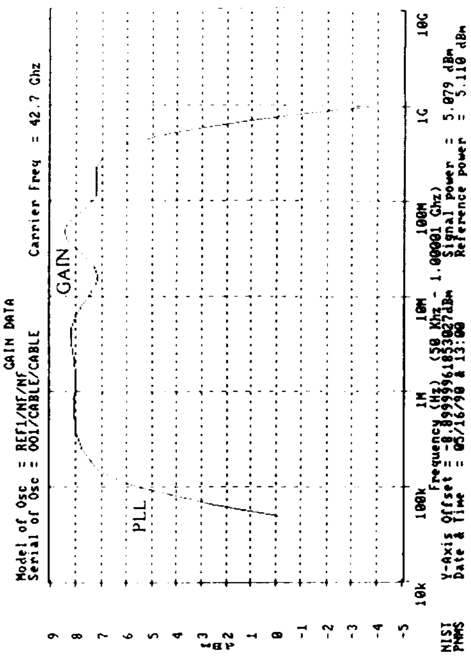
E Reference power, impedance, and cable length through B

ACCURACY OF DETERMINATION DEPENDS ON THE DEGREE ABOVE PARAMETERS HELD CONSTANT PLUS

A Linearity and slewing rate of amplifier

CALIBRATION CONDITION MUST REPLICATE THE MEASUREMENT CONDITION AS CLOSELY AS POSSIBLE

PLL AND GAIN EFFECTS ON G(f) Kd



3. PLL EFFECTS (IF ANY)

ATTENUATION OF THE LOW FREQUENCY PHASE DEVIATION CAN BE REDUCED BY

A Normal PLL loop. Results may be altered by additional filters in electronic frequency control (EFC) path

B Signals that propagate through the power sources of the two oscillators

C Signals that propagate through the air to pull the frequency of one or both signals

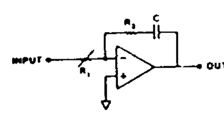
E Signals that propagate through the measurement system (mixer) to pull the frequency

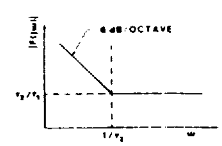
F Injection lock feedback from the cavity discriminator or delay line discriminator

PLL EFFECTS SHOULD BE MEASURED IN SITU SINCE MANY EFFECTS IN THE EFC PATH ARE HIDDEN.

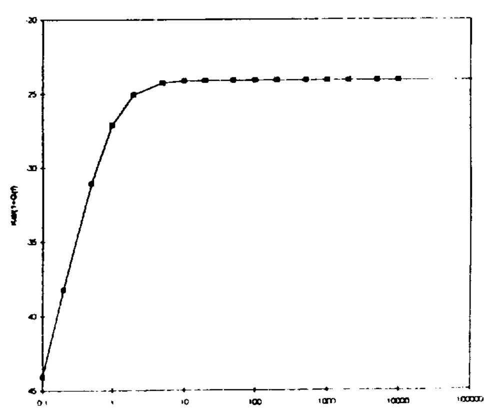
ERRORS IN PARAMETERS 1-3 ARE OFTEN CORRELATED

PLL RELATIONS

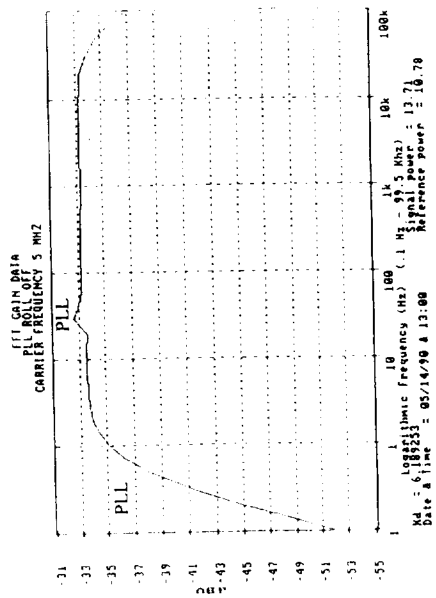




$$G(f)_{PLL} = C\frac{(1+j\omega R_2 C)}{j\omega R_1 C} \qquad V_d = \frac{K_d(\Delta\phi_{test} - \Delta\phi_{ref})}{1+G(f)_{PLL}}$$



PLL EFFECTS ON G(f) Kd



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MEASUREMENTS OF $S_\phi(f)$ @ MHz SYNTHESIZER VS OSCILLATOR

f (Hz)	$S_\phi(f)\|_{AB}$ (db/Hz)	$S_a(f)\|_{AB}$ (dB/Hz)	$S_a(f)\|_A\ \beta^2 A$ (dB/Hz)	Measured Noise Floor dB rel Rad^2/Hz	Actual Noise Floor
32	-119.8	-126.0	≈ -151.0	-154.0	-160.0
100	-124.2	-127.0	≈ -152.0	-154.0	-165.0
1 K	-132.1	-132.0	≈ -157.0	-158.0	175.0
10 K	-137.3	-133.0	≈ -158.0	-158.0	175.0
100 K	-136.8	-133.0	≈ -158.0	-158.0	175.0

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4. CONTRIBUTION OF AM NOISE

AM TO PM CONVERSION IS UNIVERSAL

A. Occurs via non-linear process

B. Typically -15 to -25 dB in double balanced mixers

C. Can reach - 3 dB in some amplifiers

D. Sets the noise floor in many measurements

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5. HARMONIC DISTORTION

A. Harmonics of signal and reference contribute to K and detected noise

B. PM noise on harmonics may not be same as fundamental

C. Sensitivity depends on power, impedance, harmonic number

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TO GET NOISE FLOOR SET A = B

$$S_\phi(f)_{Noise\ Floor} = S_{\phi A}(2\pi f\tau_{delay})^2 + \frac{V_n(f)^2_{system}}{K_d^2 BW} + S_{aA}(f)\beta_A^2 + S_\phi(f)_{power\ splitter}$$

$$(2\pi f\tau_{delay})^2 S_\phi(f) = (\tfrac{\pi}{20})^2 S_\phi(f) \quad \text{for} \quad f = \tfrac{v}{10}, \tau_{delay} = \tfrac{\pi}{2}$$

TO CALCULATE INDIVIDUAL PM NOISE FOR AN OSCILLATOR

$$S_\phi(f)_{AB} + S_\phi(f)_{AC} - S_\phi(f)_{BC} = 2S_{\phi A}(f) + \frac{V_n^2}{K_d^2 BW} + 2S_{aA}(f)\beta_A^2$$

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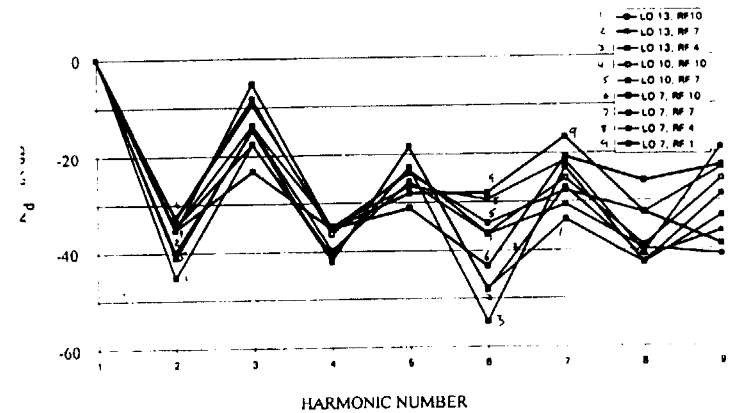
HARMONIC SENSITIVITY OF MIXER VS RF AND LO POWER IN dB



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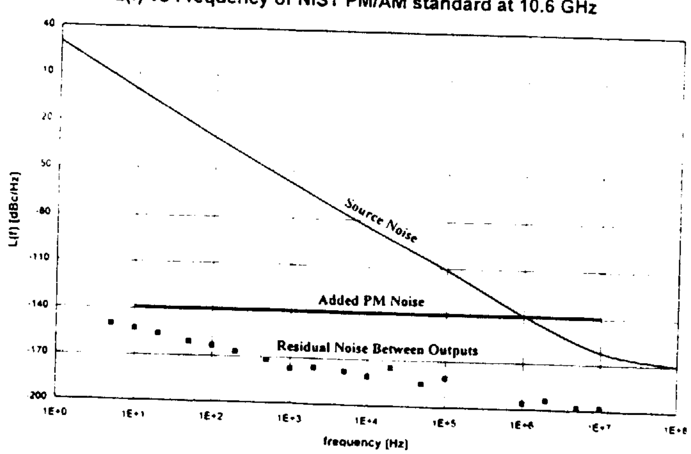
L(f) vs Frequency of NIST PM/AM standard at 10.6 GHz



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6. CONTRIBUTION OF SYSTEM NOISE FLOOR

NOISE TERMS INCLUDED IN $\frac{PSD(V_n)}{K_d^2 G(f)^2}$

$$S_\phi(f) = \frac{[\Delta\phi_A(f) - \Delta\phi_B(f)]^2}{BW} + \frac{V_n(f)^2_{mixer}}{K_d^2 BW} + \frac{V_n(f)^2_{amp}}{K_d^2 BW} + \frac{V_n(f)^2_{SA}}{K_d^2 G(f)^2 BW} + S_{aA}(f)\beta_A^2 + S_{aB}(f)\beta_B^2$$

$$S_\phi(f)_{pair} = S_{\phi A}(f) + S_{\phi B}(f) + \frac{V_n(f)^2_{system}}{K_d^2 BW} + S_{aA}(f)\beta_A^2 + S_{aB}(f)\beta_B^2$$

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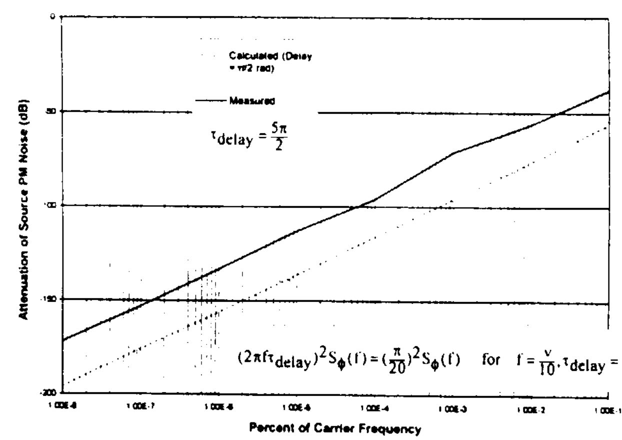
8. STATISTICAL CONFIDENCE OF THE DATA

Table 1. Approximate 68% confidence Intervals for FFT Spectral Estimates N > 10

power law noise type	uniform	window Hanning	flattened peak
f^{0}	$1.02/\sqrt{N}$	$0.98/\sqrt{N}$	$0.98/\sqrt{N}$
f^{-2}	$1.02/\sqrt{N}$	$1.04/\sqrt{N}$	$1.04/\sqrt{N}$
f^{-3}	unusable	$1.04/\sqrt{N}$	$1.04/\sqrt{N}$
f^{-4}	unusable	$1.04/\sqrt{N}$	$1.04/\sqrt{N}$

$$S = S_m\left(1 \pm \frac{B}{\sqrt{N}}\right)$$

Phase Noise added by delay line at 10.6 GHz Carrier Frequency



7. CONTRIBUTION OF REFERENCE AM AND PM NOISE

NOISE TERMS INCLUDED IN $\frac{PSD(V_n)}{K_d^2 G(f)^2}$

$$S_\phi(f) = \frac{[\Delta\phi_A(f) - \Delta\phi_B(f)]^2}{BW} + \frac{V_n(f)^2_{mixer}}{K_d^2 BW} + \frac{V_n(f)^2_{amp}}{K_d^2 BW}$$

$$+ \frac{V_n(f)^2_{SA}}{K_d^2 G(f)^2 BW} + S_{aA}(f)\beta_A^2 + S_{aB}(f)\beta_B^2$$

$$S_\phi(f)_{pair} = S_{\phi A}(f) + S_{\phi B}(f) + \frac{V_n(f)^2_{system}}{K_d^2 BW} + S_{aA}(f)\beta_A^2 + S_{aB}(f)\beta_B^2$$

STATISTICAL UNCENTAINTY OF FFT SPECTRAL DENSITY MEAUREMENTS

$S_m(f) = S(f)\,[1 \pm k/N^{1/2}]$

k = 1 → 68%, k = 1.9 → 95% CONFIDENCE N ≥ 10

N = number of samples averaged

Number of Samples	k = 1 (approx 68%) $S_m = S[1\pm\alpha]$, $S_m\,{}^{\gamma}_{\beta}$ dB			k = 1.9 (approx 95%) $S_m = S[1\pm\alpha]$, $S_m\,{}^{\gamma}_{\beta}$ dB		
	α	γ	β	α	γ	β
4	0.54	-2.	+3.3	1.5	-3.	+6
6	0.42	-1.5	+2.3	1.4	-2.5	+5
10	0.32	-1.2	+1.7	0.61	-2.1	+4
30	0.18	-0.72	+.86	0.35	-1.3	+1.8
100	0.1	-0.41	+0.46	0.19	-0.76	+0.92
300	0.058	-0.24	+0.25	0.14	-0.46	+0.51
1000	0.032	-0.13	+0.13	0.06	-0.26	+0.28
3000	0.018	-0.08	+0.08	0.035	-0.15	+0.15
10000	0.01	-0.04	+0.04	0.019	-0.08	+0.08

D. B. Percival and A. T. Walden, "Spectral Analysis for Physical Application," Cambridge Univ. Press, 1993

B. N. Taylor and C. E. Kuyatt, NIST Technical Note TN1297, 1993

STATISTICAL UNCENTAINTY OF SWEPT RF SPECTRAL DENSITY MEAUREMENTS

$S_m(f)$ = S(f)[1 + k(VIDEO$_{bw}$/NRES$_{bw}$)^{½}]

k = 1 - 68%, k = 1.9 - 95% CONFIDENCE   N ≥ 10

VIDEO$_{bw}$ = video bandwidth

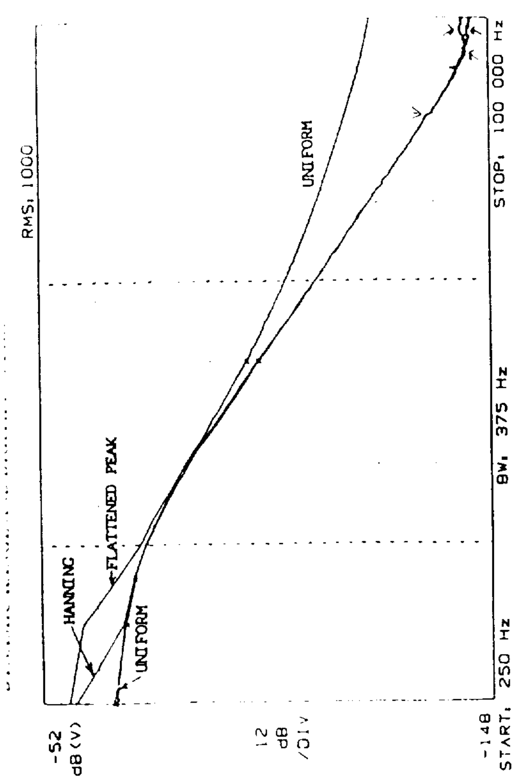
N = number of sweeps averaged

RES$_{bw}$ - resolution bandwidth ≤ f/10

NRES$_{bw}$ / VIDEO$_{bw}$	k = 1 (approx 68%) S_m = S[1±δ], S_m $^{\gamma}_{\beta}$ dB			k = 1.9 (approx 95%) S_m = S[1±δ], S_m $^{\gamma}_{\beta}$ dB		
	δ	γ	β	δ	γ	β
4	0 54	-2 ,	+3 3	2 5	-3 ,	+6
6	0 42	-1 5,	+2 3	1 4	-2 5,	+5
10	0 32	-1 2,	+1 7	0 61	-2 1,	+4
30	0 18	-0 72,	+ 86	0 35	-1 3,	+1 8
100	0 1	-0 41,	+0 46	0 19	0 76,	+0 92
200	0 058	-0 24,	+0 25	0 14	-0 46,	+0 51
1000	0 032	-0 13,	+0 13	0 06	-0 26,	+0 28
3000	0 018	-0 08,	+0 08	0 035	-0 15,	+0 15
10000	0 01	-0 04,	+0 04	0 019	0 08,	+0 08

D. B. Percival and A. T. Walden, "Spectral Analysis for Physical Application," Cambridge Univ. Press, 1993

B. N. Taylor and C. E. Kuyatt, NIST Technical Note TN1297, 1993



9. LINEARITY OF SPECTRUM ANALYZER

A. Accuracy of wide dynamic range

B. Digitizing errors

C. Need to segment spectrum with filters

10. ACCURACY OF THE PSD FUNCTION

DEPENDS ON

A. Signal type

Use flat top window for bright lines

Use Hanning window for noise

B. Window function and Fourier frequency (leakage)

f should be less than span/23 for Flat top window

f should be less than span/75 for Flat top window

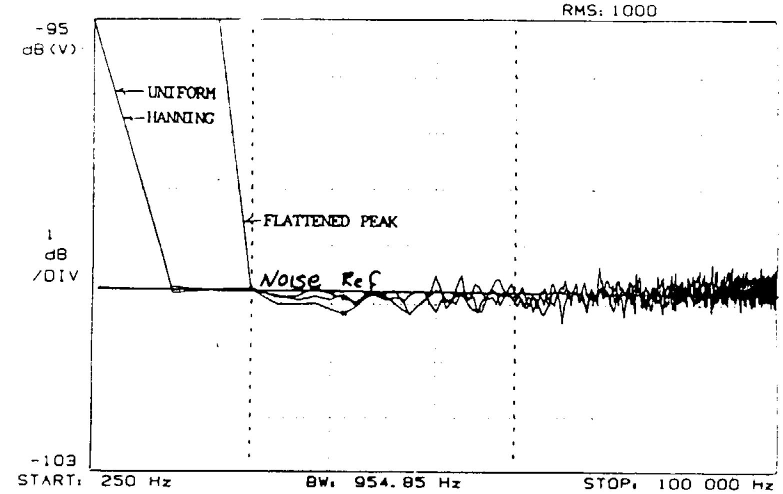
ORIGINAL PAGE IS OF POOR QUALITY

APPROXIMATE BIASES IN FFT SPECTRAL DENSITY ESTIMATORS

Channel #	Noise Type f^0 Flat Top	Noise Type f^0 Hanning	Noise Type f^0 Uniform	Noise Type f^4 Flat Top	Noise Type f^4 Hanning	Noise Type f^4 Uniform
1	20.1 dB	19.6 dB	19.6 dB	10.0 dB	8.6 dB	Not Useable
2	16.7	Small	Small	9.1	0.4	
3	7.22	↓	↓	4.0	0.4	
4	Small			1.2	Small	
5	↓			1.1	↓	
6				1.1		
7				1.0		
8				0.8		
9				0.6		
10				0.6		
11				0.5		
12				0.4		
13				0.4		
14				Small		
15				↓		

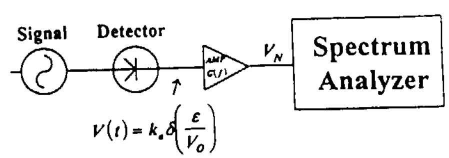
TIME AND FREQUENCY DIVISION, NIST PTTI 1994

PSD OF f^0 NOISE



TIME AND FREQUENCY DIVISION, NIST PTTI 1994

Simple AM Measurement



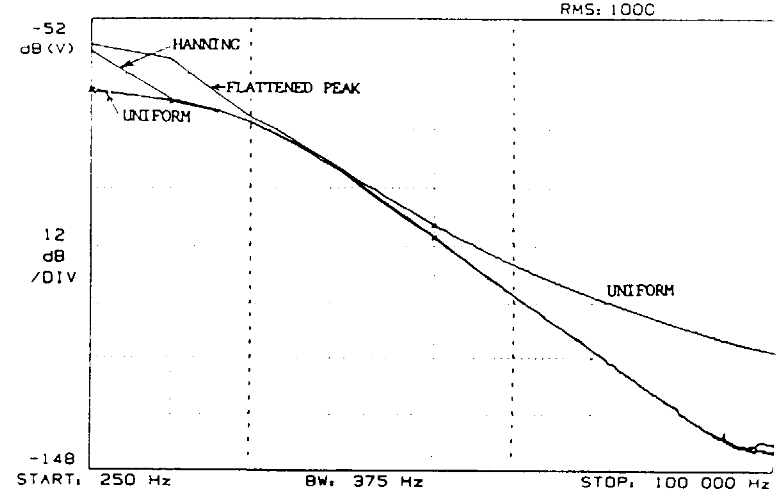
$$V(t) = k_a \delta\left(\frac{\varepsilon}{V_o}\right)$$

$\frac{PSDV_N}{[k_a G(f)]^2}$ measures $S_a(f)$ of the Signal plus the system noise.

It is difficult to seperate the system noise from a signal with low AM noise.

TIME AND FREQUENCY DIVISION, NIST

PSD OF f^4 NOISE



TIME AND FREQUENCY DIVISION, NIST

ERROR MODEL FOR AM MEASUREMENTS

1. DETERMINATION OF K
2. DETERMINATION OF AMPLIFIER G(f)
3. CONTRIBUTION OF SYSTEM NOISE FLOOR
4. STATISTICAL CONFIDENCE OF DATA
5. LINEARITY OF SPECTRUM ANALYZERS
6. ACCURACY OF PSD FUNCTION

1. DETERMINATION OF Ka

DETECTOR SENSITIVITY DEPENDS ON

A. Carrier frequency

B. Signal power and impedance

C. Detector termination both ports

D. Cable lengths

E. Fourier frequency

Sensitivity to Fourier frequency is often difficult to measure due to bandwidth of most AM modulators

CALIBRATION CONDITION MUST REPLICATE THE MEASUREMENT CONDITION AS CLOSELY AS POSSIBLE

2. DETERMINATION OF AMPLIFIER G(f)

Depends on

A. Detector output impedance

B. Signal power, impedance, and cable length through A

C. Fourier frequency

CALIBRATION CONDITION MUST REPLICATE THE MEASUREMENT CONDITION AS CLOSELY AS POSSIBLE

3. CONTRIBUTION OF AM SYSTEM NOISE FLOOR

A. Noise floor difficult to measure in single channel systems

B. Cross-correlation can be used to determine noise floor (part III)

CALIBRATION CONDITION MUST REPLICATE THE MEASUREMENT CONDITION AS CLOSELY AS POSSIBLE

MODEL FOR PM IN AMPLIFIERS

PM AM

$$S_\phi(f) = \left[\frac{\alpha_E}{f} + \frac{2kTFG}{P}\right] \Rightarrow S_a(f)$$

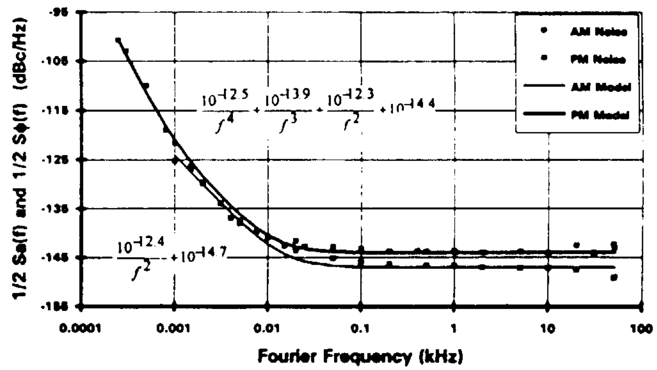
NEW

LEESON'S MODEL FOR PM IN OSCILLATORS

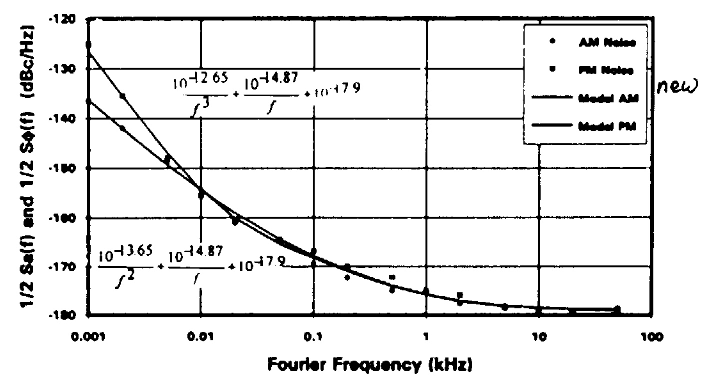
$$S_\phi(f) = \left(\frac{\upsilon_0}{2Q_L}\right)^2 \frac{1}{f^2}\left[\frac{\alpha_E}{f} + \frac{2kTFG}{P}\right] + \left[\frac{\alpha_E}{f} + \frac{2kTFG}{P}\right] + \left(\frac{\upsilon_0}{2Q_L}\right)^2 \frac{1}{f^2}\left[\frac{\alpha_R}{f}\right]$$

	Amplifier		Resonator
$BW = \upsilon_0/2Q_L$	f<BW	f>BW	f<BW

5 MHz AM and Phase Noise



5 MHz AM and PM Noise



NOISE MODEL OF AMPLIFIERS

AM and PM similar 1/f + thermal

NOISE MODEL OF OSCILLATORS

PM complicated-see examples

PM typically includes $1/f^3$ + thermal

AM depends on circuit and degree of limiting

AM sometimes 1/f + attenuated thermal

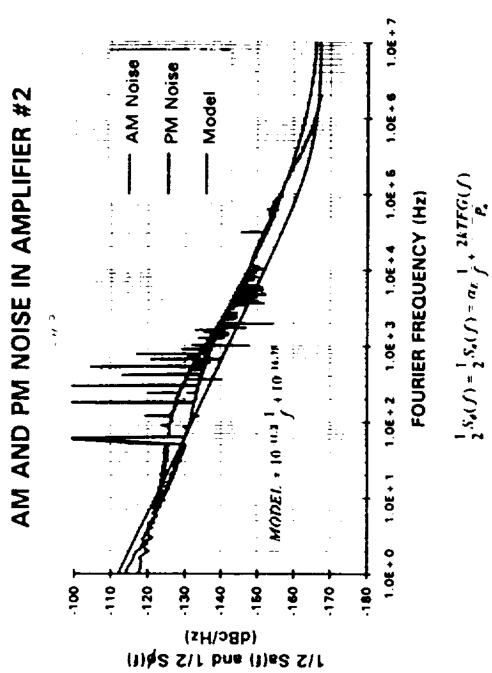
NOISE MODEL OF PM MEASUREMENT SYSTEMS

1/f + thermal for two oscillator type

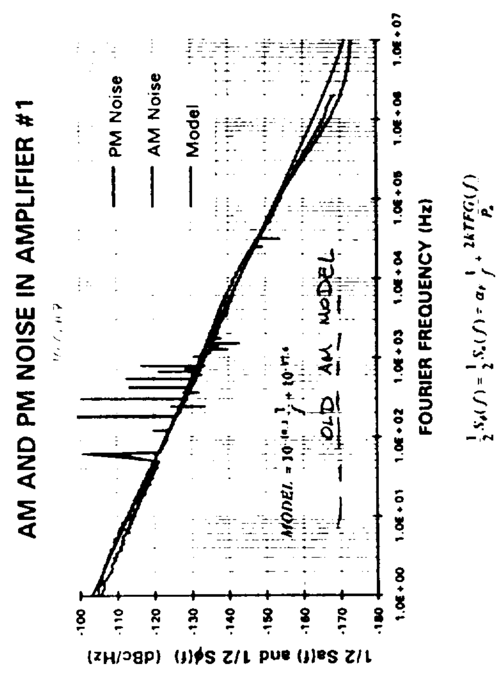
$1/f^3$ + thermal for single oscillator type

NOISE MODELS OF AM DETECTORS

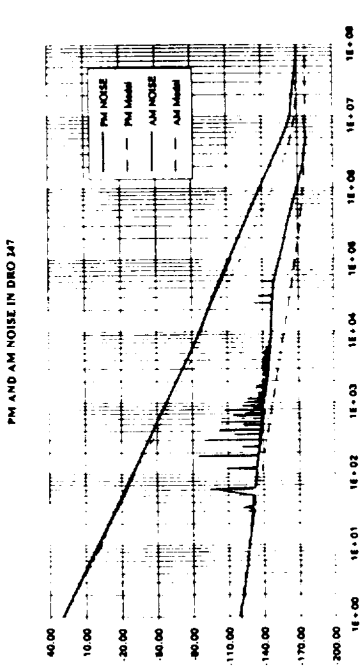
1/f + thermal



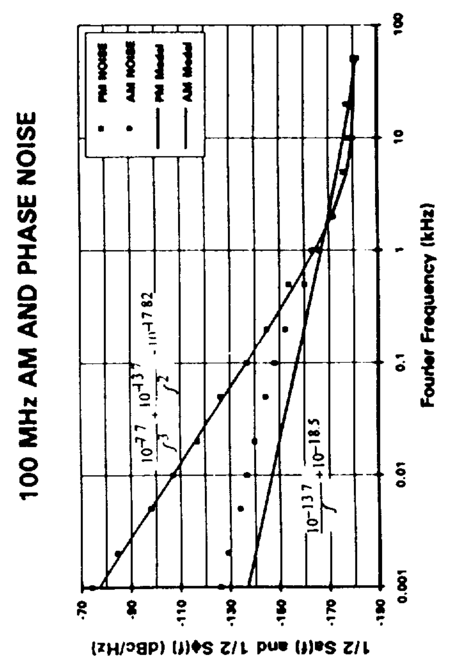
AM AND PM NOISE IN AMPLIFIER #2
AM Noise
PM Noise
Model
FOURIER FREQUENCY (Hz)
1/2 Sa(f) and 1/2 Sφ(f) (dBc/Hz)



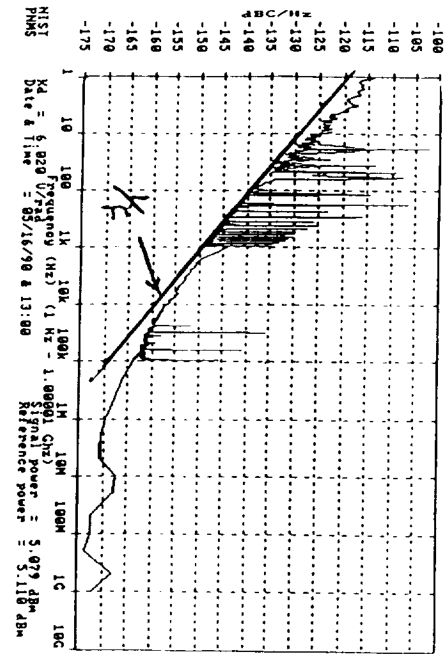
AM AND PM NOISE IN AMPLIFIER #1
PM Noise
AM Noise
Model
OLD AM MODEL
FOURIER FREQUENCY (Hz)
1/2 Sa(f) and 1/2 Sφ(f) (dBc/Hz)



PM AND AM NOISE IN DRO 347
PM NOISE
PM Model
AM NOISE
AM Model
FREQUENCY (Hz)

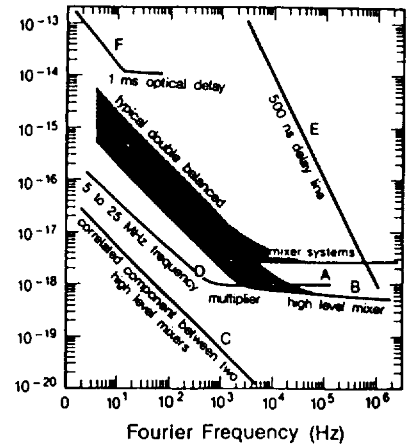


100 MHz AM AND PHASE NOISE
PM NOISE
AM NOISE
PM Model
AM Model
Fourier Frequency (kHz)
1/2 Sa(f) and 1/2 Sφ(f) (dBc/Hz)



NOISE FLOOR OF WIDE-BAND NIST PM MEASUREMENT SYSTEM AT 42 GHz

Comparison of Noise Floor for Different Techniques



PHASE NOISE RELATIONSHIPS

$$S_\phi(f) = \mathscr{L}(\nu_o - f) + \mathscr{L}(\nu_o + f)$$

$$dBC/Hz = 10 \log \mathscr{L}(f)$$

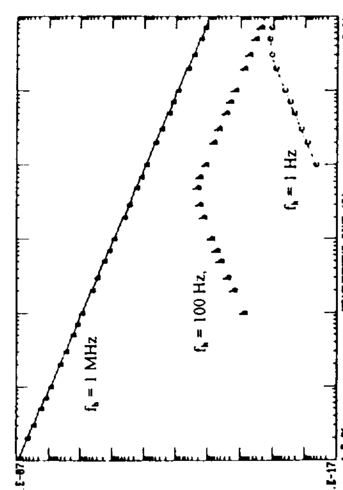
$$S_\phi(f) = \frac{\nu_o^2}{f^2} S_y(f) \quad rad^2/Hz \quad 0<f<\infty$$

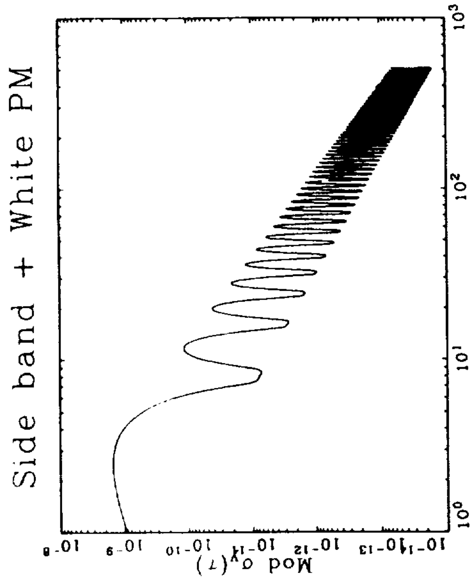
$$\sigma_y^2(\tau) = 2\int_0^\infty df\, S_y(f) \frac{\sin^4(\pi f\tau)}{(\pi f\tau)^2}$$

$$Mod\ \sigma_y(n\tau_o) = \left(\frac{2}{n^2(\pi n\tau_o)^2} \int_0^{f_h} S_y(f) \frac{\sin^6(\pi f n\tau_o)}{f^2\sin^2(\pi f\tau_o)}\, df\right)^{1/2}$$

CONVERSION OF $S_\phi(f)$ TO $\sigma_y(\tau)$ FOR

$$S_\phi(f) = \frac{4X10^{-16}}{f} + 1X10^{-17} \text{ AT 100 MHz}$$





C-4.

Discussion of Error Models for PM and AM Noise Measurements

TUTORIAL – QUESTIONS AND ANSWERS

Note from the editor

The questions were asked at various points during the presentation. They were transcribed and are presented here at the end of each tutorial.

RICHARD KEATING (USNO): I have a problem with what you mean by "harmonic distortion." Do you mean just simply the amount of power in the upper harmonics? Do you mean that a harmonic is just something that is some integer multiple of the fundamental? Or, do you refer to it as a partial? Do you mean something like that which is used in audio terminology where they talk about the "total power in the upper harmonics as being a distortion?" In short, what do you mean by "harmonic distortion?" Am I being clear?

FRED WALLS (NIST): Yeah, you're being perfectly clear. And I wasn't very clear on purpose. And the reason for that is convenience I guess. You can say "harmonic distortion," or you can say "The second harmonic is minus 25 dBc, the third harmonic is minus dBc," etcetera; and I'm just trying to show you this is the relative K_d. The sensitivity of the mixer to read out those harmonics in the signal, given an LO of a particular size, as a power ratio, relative to the fundamental. I've normalized the sensitivity of the fundamental to be zero dB or one.

And so you can see that I can change the sensitivity to, say, the third harmonic by 20 dB, depending how I tune LO and RF. And it's easy to see here, it's very clear that there's an even/odd-kind of symmetry, namely the even orders are typically much less sensitive than the odds; but I can point this one out to you where, in fact, the fifth and sixth have about the same sensitivity. And the other thing that's clear is, as you go to higher and higher harmonics, that the difference between odd and even tends to kind of wash out. And by tuning, you can make quite a difference here, 20, 25 dB. And some mixers will be better than others, low-level mixers will be different than high-level mixers, etcetera. And it's a complicated structure, but it's something you need to be aware of.

Now you can use it to your advantage. Sometimes you want to measure the phase noise of signal up here, and that's the LO that you have. And if you tune it, you can see that you can do the ninth harmonic with a penalty of only 20 dB. Maybe that's enough to get it done, maybe it isn't. And, in some cases, you can actually run up to the 25th or the 45th, or whatever; what you pay is in the noise floor.

STATE-OF-THE-ART MEASUREMENT TECHNIQUES FOR PM AND AM NOISE

Craig Nelson
SpectraDynamics Inc
(303) 497-3069
email: nelson@boulder.nist.gov

PTTI 1994 1

State-of-the-art measurement techniques for PM and AM noise

- Ultra wideband measurements (Fourier frequencies 0.1Hz to 1 GHz)
- Integral PM and AM noise standards
- Ultra low-noise PM and AM measurement systems ($S(f) \leq -190$ dBc/Hz)

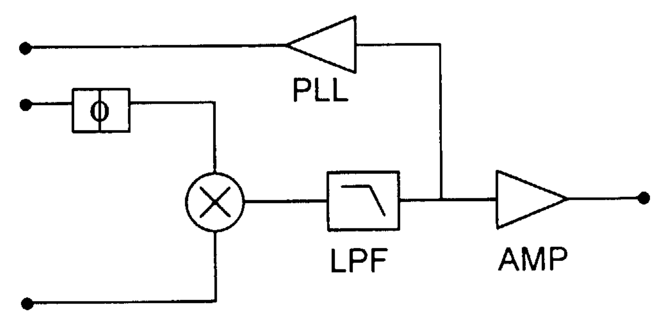
PTTI 1994 2

NIST PM/AM noise measurement system

- Separates PM from AM noise
- Measures carrier frequencies from 5 MHz to 75 GHz
- Extends Fourier analysis to 1GHz
- Measurement accuracy: 0.3 - 3 dB
- Calibrates most PM/AM measurement error models

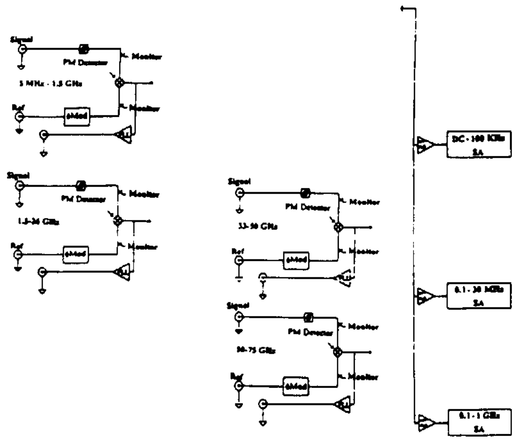
PTTI 1994 3

Basic phase noise measurement



PTTI 1994 4

NIST wideband measurement system



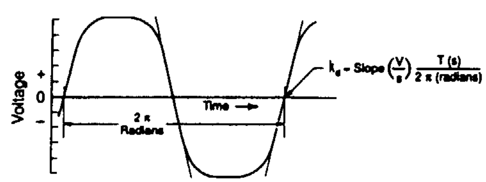
PTTI 1994 5

NIST modulator

- Can be adjusted for pure PM or AM modulation
- Extremely flat frequency response
- Calibrates Kd(f) with system locked

PTTI 1994 7

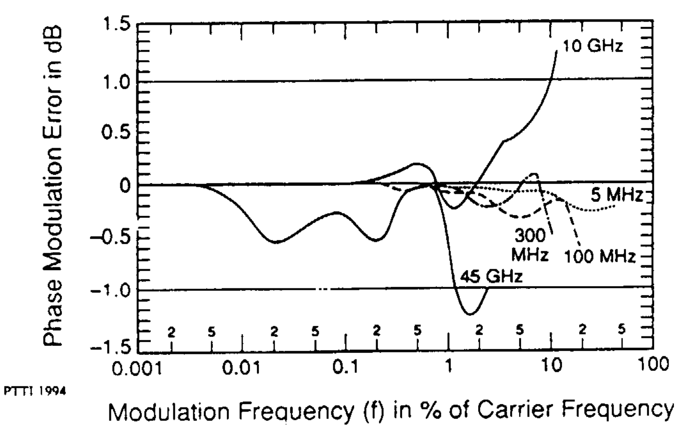
Determination of Kd



- Determines Gain at single frequency
- Does not calibrate pll effects

PTTI 1994 6

Errors in the NIST modulator



PTTI 1994 10

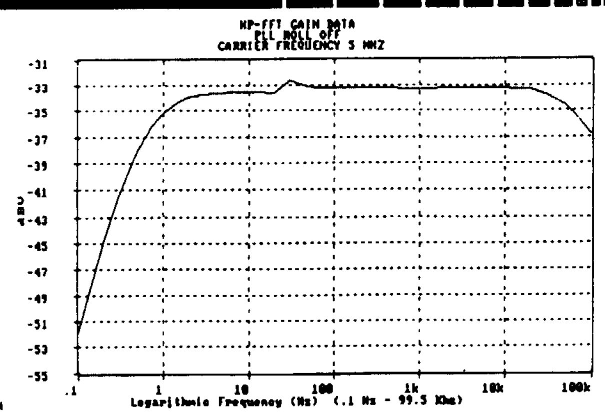
Tips for measuring gain Vs Fourier frequency

- Measure power spectrum not PSD
- Use flattop windows for FFT
- Only small number of averages required
- Use zero span width on spectrum analyzers
- 3-5 points per decade
- create gain curve with cubic spline

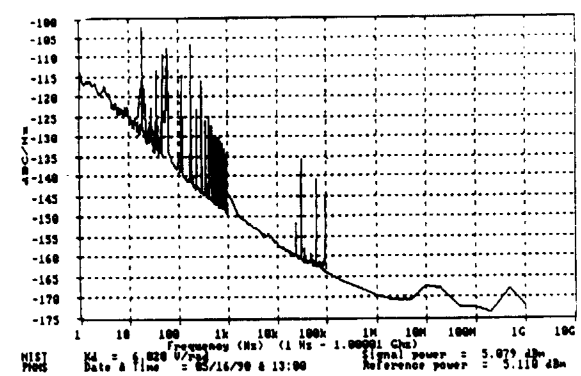
Tips for measuring noise

- Use PSD on FFT
- Using Hanning window
- Confidence interval depends on number of averages
- Confidence interval depends also on resolution and video bandwidth for swept analyzers
- Keep level of system noise floor in mind

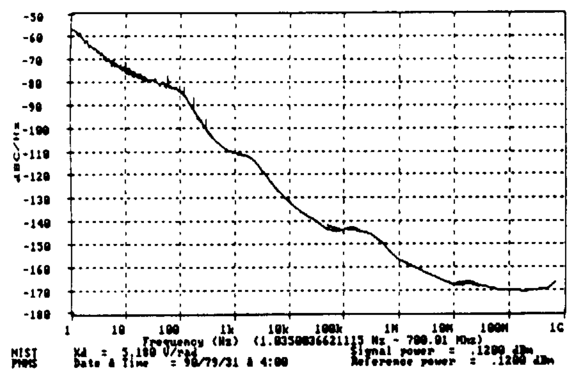
Sample gain curve at X-band



Noise floor of NIST system at 42 GHz



Phase noise of X-band synthesizer



PTTI 1994 15

Current performance of NIST phase noise measurement system

Noise Floor	Accuracy
5 to 1500 MHz	
-140 dBc/Hz at 1Hz	±0.5 dB 1Hz to 32 MHz
-173 dBc/Hz Floor	±1 dB 32 MHz to 150 MHz
1.5 to 26 GHz	
-135 dBc/Hz at 1 Hz	± 1dB 1Hz to 500 MHz
-170 dBc/Hz Floor	±2 dB 500 MHz to 1GHz

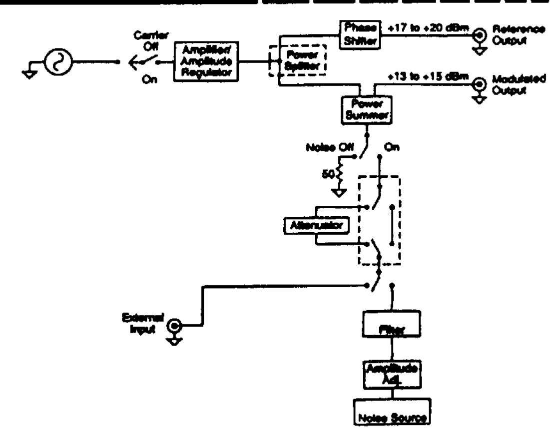
PTTI 1994 16

Integral PM and AM noise standards

- Low noise signal source
- Two outputs with extremely low differential AM and PM noise
- Calibrated noise source
- Greatly simplifies AM and PM measurements

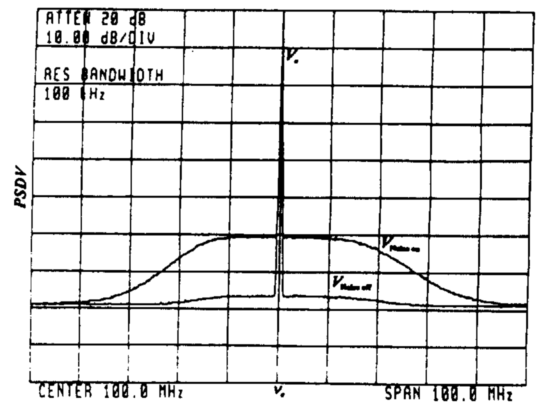
PTTI 1994 18

Block diagram of NIST PM/AM noise standard



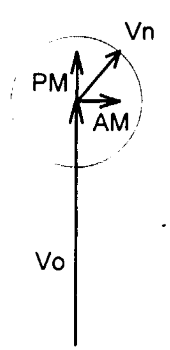
PTTI 1994 19

Addition of noise to carrier



PTTI 1994 20

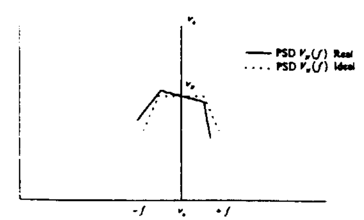
Added noise appears as equal amounts of AM and PM



$$S_a(f) = S_\phi(f) = \frac{PSDV_n(\nu_0 - f) + PSDV_n(\nu_0 + f)}{2V_0^2}$$

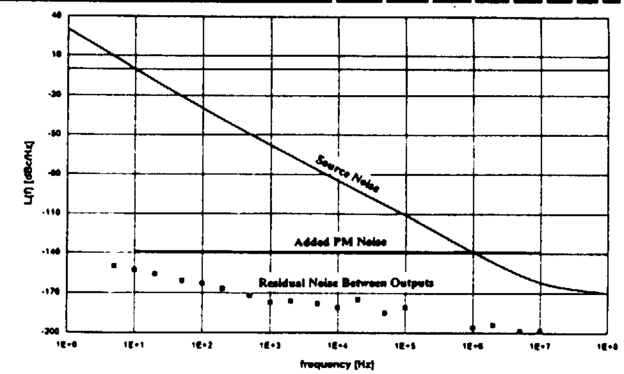
While

$$\int_0^\infty S_\phi(f) << 0.1$$



PTTI 1994 21

Phase noise of NIST X-band PM/AM standard



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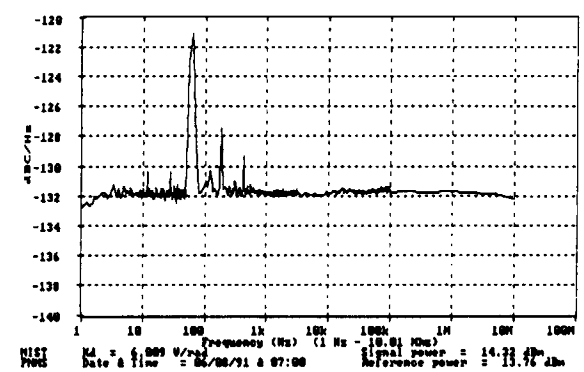
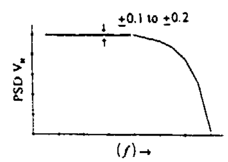
Added PM noise at 100 MHz



PTTI 1994 23

Stability of noise standard

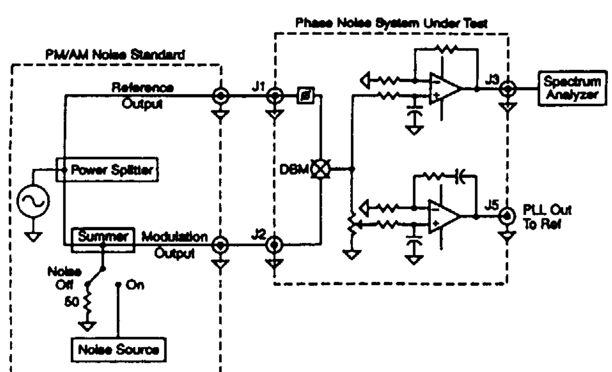


$$\frac{dS_\phi(f)}{dTemp} < 0.02\,dB/^{\circ}C$$

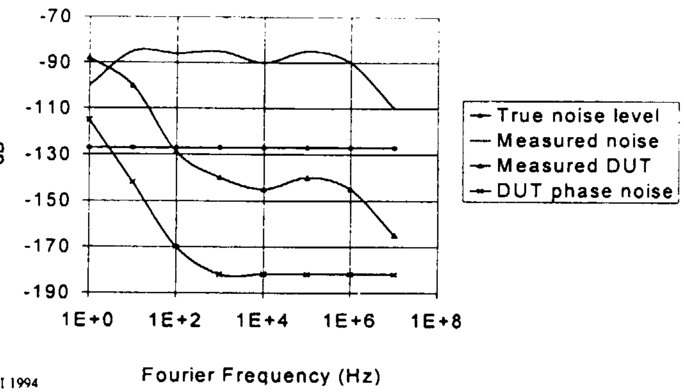
$$\frac{dS_\phi(f)}{dtime} < 0.2\,dB/year$$

$$accuracy/_{calib.} \pm 0.15dB$$

System noise floor for PM



Use of noise calibration level



Calibration of noise floor and system accuracy

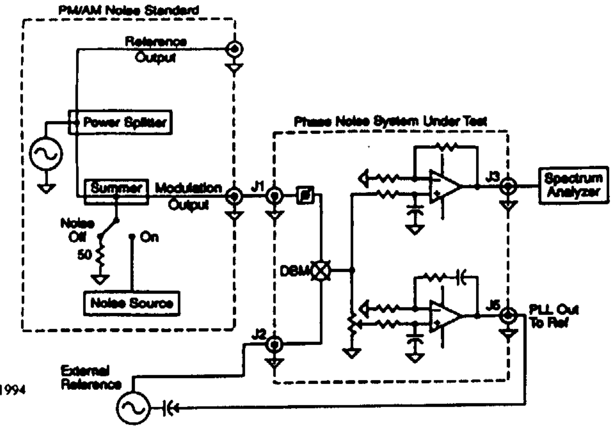
MAXIMUM RESIDUAL NOISE BETWEEN CHANNELS dBc/Hz

SOURCE FREQUENCY	1 Hz	10 Hz	100 Hz	1 kHz	10 kHz	100 kHz	1 MHz	10 MHz
5 MHz	-162	-172	-182	-190	-194	-191		
10 MHz	-161	-176	-183	-191	-197	-194		
100 MHz	-152	-162	-172	-182	-193	-193	-194	
10.6 GHz		-153	-163	-173	-181	-181	-196	-198

DIFFERENTIAL PM/AM NOISE LEVEL ± 0.2 dBc/Hz

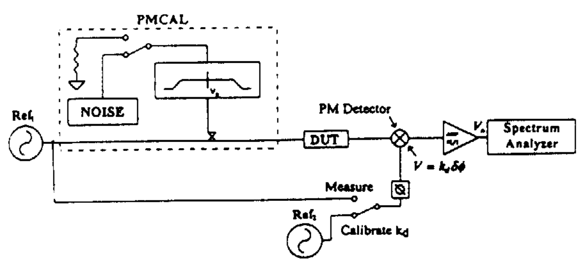
SOURCE FREQUENCY	1 Hz	10 Hz	100 Hz	1 kHz	10 kHz	100 kHz	1 MHz	10 MHz
5 MHz	-127.3	-127.3	-127.3	-127.3	-127.3	-127.3		
10 MHz	-128.4	-128.4	-128.4	-128.4	-128.4	-128.4	-128.4	
100 MHz	-129.5	-129.5	-129.5	-129.5	-129.5	-129.5	-129.5	-129.8
10.6 GHz	-138.9	-138.9	-138.9	-138.9	-138.9	-138.9	-138.9	-138.9

Measurement of an external oscillator



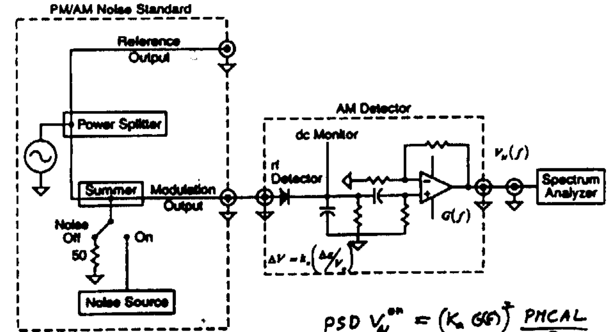
PTTI 1994 28

Measurement of other devices



PTTI 1994 29

Calibration of a simple AM measurement

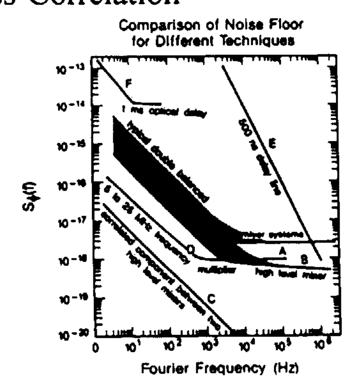


$$PSD\ V_N^{en} = (K_a\, G(f))^2\, \frac{PMCAL}{2}$$

PTTI 1994 30

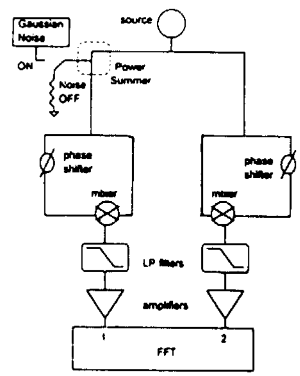
Ultra low PM and AM measurement systems

- Cross-Correlation



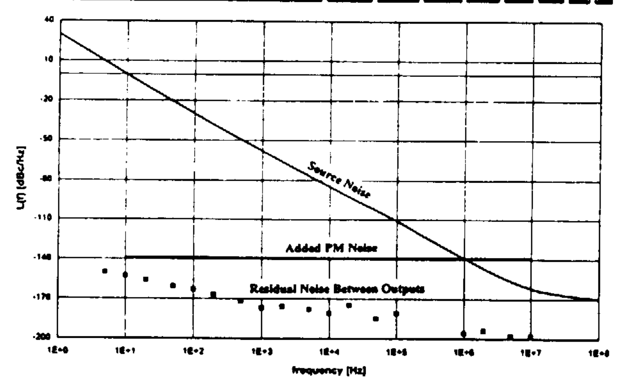
PTTI 1994 31

Cross-correlation PM noise floor measurement



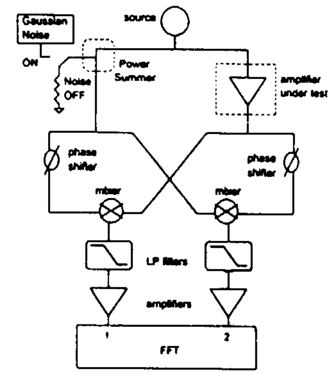
PTTI 1994 32

Residual noise between channels of NIST phase noise standard



PTTI 1994 33

Cross-correlation PM noise system for amplifier measurements



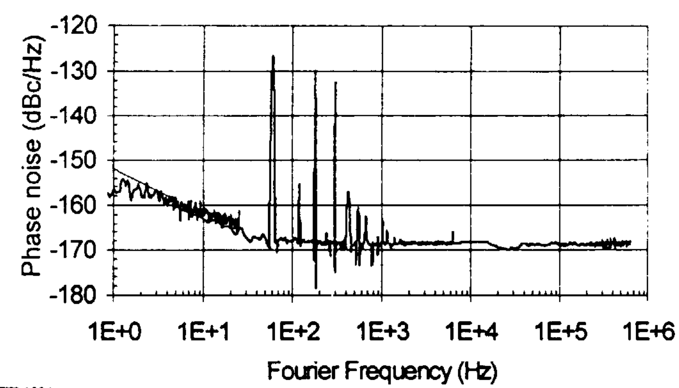
$PSD1 = PM_{amplifier} + NOISE_{channel1}$

$PSD2 = PM_{amplifier} + NOISE_{channel2}$

$PSD(CROSS) = PM_{amplifier}$

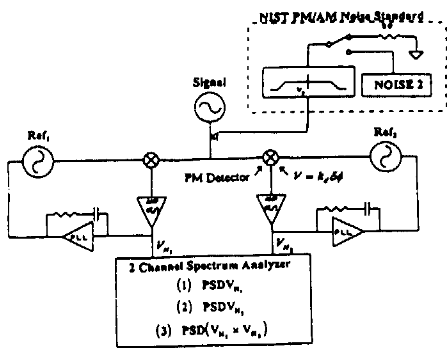
PTTI 1994 34

Ultra-low noise amplifier measurement

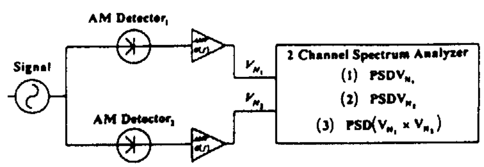


PTTI 1994 35

Cross-correlation oscillator measurements



Cross-correlation AM measurements

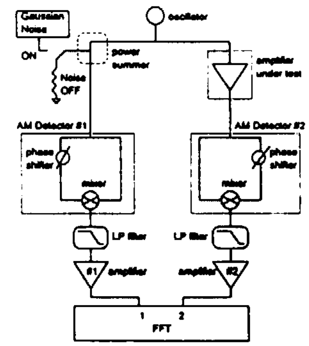


(1) $\dfrac{PSDV_{N_1}}{[k_d G(f)]^2}$ measures $S_a(f)$ of the signal plus System$_1$ noise.

(2) $\dfrac{PSDV_{N_2}}{[k_d G(f)]^2}$ measures $S_a(f)$ of the signal plus System$_2$ noise.

(3) $\dfrac{PSD(V_{N_1} \times V_{N_2})}{[k_d G(f)]^2}$ measures $S_a(f)$ of only the signal since, System$_1$ noise is uncorrelated with System$_2$ noise.

Cross-correlation AM amplifier measurements



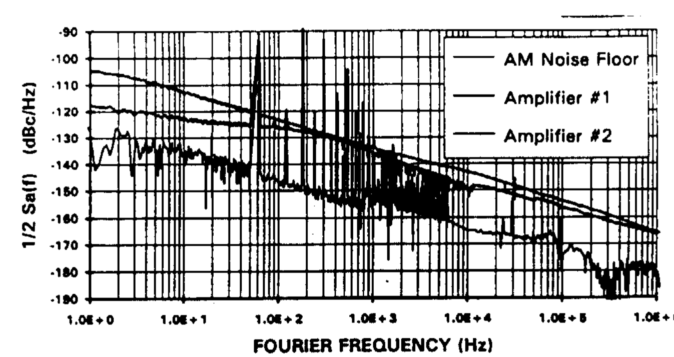
$PSD1 = NOISE_{channel\ 1} + AM_{source}$

$PSD2 = NOISE_{channel\ 2} + AM_{source} + AM_{amplifier}$

$PSD1 - PSD2 = AM_{amplifier} + NOISE_{channel\ 1} - NOISE_{channel\ 2}$

$PSD(CROSS) = AM_{source}$

Noise floor of AM measurement system



Conclusions

- To increase Fourier range a modulation technique (PM or FM) can be used.
- Using an added noise source greatly simplifies PM and AM measurements as well as decreases measurement times.
- For ultra-low noise floors cross-correlation techniques must me used.

State-of-the-Art Measurement Techniques for PM and AM Noise

TUTORIAL – QUESTIONS AND ANSWERS

Note from the editor

The questions were asked at various points during the presentation. They were transcribed and are presented here at the end of each tutorial.

JEFF INGOLD (ALLIEDSIGNAL TECHNICAL): Does each spectrum analyzer have its own amplifier?

CRAIG NELSON (SPECTRADYNAMICS): Yes. We use a different amplifier for all of the spectrum analyzers.

JEFF INGOLD (ALLIEDSIGNAL TECHNICAL): And what kind of noise figure?

CRAIG NELSON (SPECTRADYNAMICS): I'm not sure on the actual noise figures of the separate amplifiers. But that all, in a sense, washes out, when we do the noise floor of the amplifier. Well, it's important in the design, obviously.

JEFF INGOLD (ALLIEDSIGNAL TECHNICAL): The overlap in the data, is that the cross–correlation between spectrum analyzers?

CRAIG NELSON (SPECTRADYNAMICS): Yes. Actually, we generally use several frequency spans in the measurements. For this measurement, we probably use a 25 Hz span that covers about to here on the FFT; then we probably use the 400 Hz span, a 1 kilohertz (kHz) span, and a 100 kHz span. And at this point, you can see the selective level meter takes over; and then finally, here the spectrum analyzer takes over.

Now when we sweep the space–modulated signal across, we measure it on all different instruments on the different analyzers. And we measure the same point. And then we can use that to cross the calibration over to different instruments. Then you can see they match up extremely well with this method.

RALPH PARTRIDGE (LOS ALAMOS): You seemed quite confident that you knew that those larger errors were due to the non–linearity in the analyzer. How do you come about that?

CRAIG NELSON (SPECTRA DYNAMICS): Well the error terms are error terms that we calculate, they're not absolute error terms. We measure value; we don't absolutely know what the true value is. So, it's an error analysis that we do through all the system. We figure there is a certain error budget to each term, and we sum those up.

FRED WALLS (NIST): The column there on the right is the confidence for the measurements, not the errors. Because if they were errors and we knew about them, we just back them out and measure it. But that's the sum of the errors from the modulator, the demodulator, the amplifier gains, POLs – wouldn't affect that.

I know it's been a really long session, but do you have any more questions? The one thing that a phase noise standard does not handle is the AM to PM conversions. That's one of the errors that one would have to measure independently.

JEFF INGOLD (ALLIEDSIGNAL TECHNICAL): Could you back up to, I think it was 36? I can see A to B and A to C; but I don't quite see B to C on the three–corner hat. Could you expand a little bit?

CRAIG NELSON (SPECTRADYNAMICS): Well the B to C doesn't really happen.

FRED WALLS (NIST): And it's not needed?

CRAIG NELSON (SPECTRADYNAMICS): It's not needed, because the noise – I'm not saying you get all three of those measurements. With this technique, you only get the noise of the signal source. If you want the noise of all three oscillators, you still have to end up doing measurements. But frequently, you have to measure three oscillators just to get the absolute noise of a single oscillator. Does that answer your question?

JEFF INGOLD (ALLIED SIGNAL TECHNICAL): Yes.

FRED WALLS (NIST): All right, basically the noise in this measurement system and the noise in this reference are uncorrelated with the noise in this measurement in this measurement system. And so when you do the PST of the cross, those noise terms average to zero as one over the square root of the measurements, and they simply drop out. And the fact that the measurements are made simultaneously, then fluctuations in the various ones also cancel better in the noise floors, quite a bit better than what you can get if you did the actual three–corner hat sequentially.

The other difference is when you do the three–corner hat sequentially, you end up subtracting large numbers to get a little one; and so, a small error gets magnified by how much better the oscillator is. In this case, a small error in the calibration here is a small error in the final result, and not magnified by the difference.

MALCOLM CALHOUN (JPL): Do you have any preference between high–level mixers and low–level mixers in your phase noise measurement systems?

FRED WALLS (NIST): It depends on the power of the source. If I have quite a bit of power, then a high–level mixer gives me a little lower noise floor. If I have a small signal, then a low–level mixer will give me a better noise floor.

PANEL DISCUSSION: Joint Defense Laboratories (JDL) Timing Research Status

MODERATOR
Edward D. Powers, jr.
U.S. Naval Research Laboratory

PANEL MEMBERS:

John R. Vig
U.S. Army Research Laboratory
and
Ronald L. Beard and Frederick E. Betz
U.S. Naval Research Laboratory

EDWARD D. POWERS (NRL): Good morning, everyone. We're going to start this morning off with a panel discussion on the Joint Defense Laboratory (JDL) Timing Research Status. We're going to talk a lot about what is Reliance and what does "Reliance" mean.

Our panel today is going to be Fred Betz from the Naval Research Laboratory (NRL), Ron Beard from the NRL and John Vig from the U.S. Army Research Laboratory (ARL). Dr. Ken Johnson was unable to attend today. We're also going to leave the floor more or less open for questioning throughout the whole panel discussion.

Let me turn it over to Fred Betz to start the discussion on his experience with what is Reliance. He's been on many panels for Reliance over the last few years, and he has quite a bit of knowledge about that. Fred.

FREDERICK E. BETZ (NRL): I don't have a prepared speech. I did get involved in the Reliance Program when my manager volunteered me a couple years ago, in 1990, to pick up when the Navy finally decided to get aboard Reliance. I understand the Army and the Air Force had gone through a Reliance type of activity. Finally, the Navy decided that maybe this was going to happen, and they had better join with the Army and Air Force.

In reality, it kind of all started when the Office of the Secretary of Defense, back in 1990, prepared a draft memorandum that said that they would take over all Science and Technology (S&T) funding activities for the three services. Perhaps for the first and only time in history the three-service principal S&T flag officers stood up and screamed in unison "No, let us do

it. Give us the rope and let us form our own noose that we may hang ourselves."

So they formed a Joint Directors of Laboratories, which is composed of the three principal S&T flag officers for the three–services panel to investigate how they could meet the Department of Defense (DoD) objectives, which were to eliminate redundancy, promote joint activity, and, of course, I guess the redundancy and the perception that everybody was going their own way in doing what they would like in research, science and technology, without any guidance. A taxonomy was established – I'm not exactly sure how that came about. I got to be on the Space Panel, being a representative from the Naval Center of Space Technology.

At that time, there was also an astrometry panel. That was seeded, at that point in time, as a result of the determinations by the Reliance groups to the Navy, and basically with the U.S. Naval Observatory (USNO) being the principal actor in astrometry. The NRL had retained space clocks, and Dr. Vig retained frequency control technology. He'll talk about that.

That is kind of the history. We went on for about three years, as I remained on the Space Panel, and not doing any real planning (to a very large extent), but more or less documenting the execution of the funding of science and technology. There were not a large number of true joint programs developed, although there were a number of small programs; and there were a number of good relationships that developed between the three representatives of the three services, in their technical areas. Instead of an environment like this in conferences, it was actually going to the residences of the laboratories of three services; and meeting, and working together, and looking at what each other were doing.

JOHN VIG (ARL): When this Reliance was initially created, my lab director came back and told us what had happened. And basically, the pie supposedly got carved up in a way that the three services each had a significant activity and area, like solid state technology, for example. Then it became, I believe it was, the Category I Program, where each service will continue doing research in a certain area; and there will be very close collaboration; and "jointness" was the key word; everything would be done jointly; that there would no Army solid state program or Air Force solid state program or Navy solid state program. All the programs shall be planned jointly and executed jointly, even though the funding might come from only one of the three services. So we were to be one big happy family, without the actual combination of the three services laboratories.

In frequency control technology, the Army was given what was called "Category III" responsibility, which meant that the Army had lead laboratory status within DoD for frequency control technology. When we first heard that, we thought that it was great news for us, we're golden, we're going to be the lead laboratory. Unfortunately, it didn't turn out that way. Because of that, the Air Force, about that time, completely got out of frequency control; the Navy's funding, I guess, was cut to zero in frequency control; and the Army's funding was cut also. So instead of it helping the technology, I think it actually hurt us quite badly.

We were given frequency control; the Navy, for example, was given vacuum electronics; technology was a Navy Category III program. The Air Force was given antenna technology as an Air Force Category III program. But each of the three services continued to do service specific research in those areas.

This summer at the annual reviews, all the different electrotonic devices programs presented an annual review before a high–level DoD person, Dr. Susan Turnbach. I gave the presentation for frequency control technology. I pointed out that the technology has declined substantially since Reliance was created. I mentioned that, for example, ten years ago there were somewhere between 50 and 100 researchers in this area, because all three services had a significant program. The Air Force had a large program in frequency control technology; they were growing quartz sponsoring research and rubidium standards and various other technologies. The Navy had a significant program and the Army had a significant program. Today, the Army is the only one with an in–house 6.1, 6.2 activity in frequency control technology. The Navy and the Air Force have no 6.1, 6.2 programs. 6.1 is basic research, 6.2 means exploratory development, applied research, basically.

Apparently my briefing caught Dr. Susan Turnbach's and AGED'S attention; and as a result, I learned recently – well, let me backtrack a second. Every year there are one or two technology areas selected for a special study, to determine what the DoD's investment strategy should be in those technologies. This year the AGED selected frequency control technology as one of two technologies. So there will be a very high–level study done on what the DoD's investment strategy should be for frequency control technology. I was asked to draft a statement of work for that study and to recommend people who should be participants in that study. I recommended some of you as participants. Potentially, this could be very helpful to us if we do a good job.

RONALD L. BEARD (NRL): I think the real significance in this overall effort is that the direction within DoD seems to be towards focused programs like this and joint operation, such that DoD isn't spending a lot of money in duplicative efforts, and things like that, which is one of the words that was used when this was initially formed. I think it is significant to point out that when it was initially formed, too, what they looked at was work that was actually being done in-house within the government, rather than contracted efforts. It was through that mechanism whether to assign the lead laboratories and the focus centers for this technology.

But in this role of combining and doing joint DoD–type procurement and development, where does the role of time and frequency fall? Well, it's almost slipped through the margins, I think, as John was pointing out. This technology is viewed by many authorities within DoD as just kind of a black–box thing that you buy off the shelf. Come to a conference like this and get a catalog from the vendor, and you just buy one. The care and feeding of the technology and development isn't really appreciated, I think, very much beyond this community. How this community can affect the long–range planning by DoD and other agencies can bear an important part on how well this technology flourishes.

I think that is one of the significant things that we need to discuss this morning, is where is this technology going; how does it contribute to the long–range plan; and should it be a significant thing to be pointed out in some of these high–level technology development areas? Otherwise, within DoD, it will get submerged behind the new extra smart sensor, the new weapon system that blows up astroids, or things like that.

I personally think that it's a very significant technology that transcends the individual systems. It's an intersystem technology, if you will. Too many system developers and technology developers

look at individual systems and specific devices to do that mission, a new sensor, something where they can see trees from the other side of the world, or something like that. Time and frequency goes across all systems, and it's difficult to get people to appreciate that. Many of them simply take it for granted. And, as I think we all know, it's not something you can really take for granted; it needs to be nurtured and developed. Significant developments have been made in this area.

FREDERICK BETZ (NRL): Ron, one of the problems with the funding for science and technology that have been incorporated under the JDL Reliance is that it only addressed the service S&T funds, which were probably about one–third of the total defense research technology budget. The vast majority, the other two–thirds, went to both the Strstegic Defense Initiatives Office (SDIO) at the time, and later, Ballistic Missile Defense Office (BMDO), and also, Advanced Research Projects Office (ARPA). There is a move afoot, at this point in time, towards getting more involvement of Director Defense Research & Engineering (DDR&E) ; it's largely in turmoil at this point in time. There was a meeting of the JDL in August where Mr. Brachkosky from DDR&E was there, and essentially agreed to be a major participant in not the JDL Reliance, but in Defense Science and Technology Reliance. So it may even have a new name before very long. That would, again, tend to centralize the control and centralize the funding, if, indeed, as proposed, ARPA and SDIO funds were swept into this area.

As was mentioned, the Navy funding of Science and Technology went away for the GPS area. Fortunately, we're a reimbursable laboratory, and Ron went out and found "customers," Space Command (SPACECOM), I guess, and some others to provide funds to keep the organization growing. His science and technology staff in precision timing are still quite robust.

I might also mention that Ron mentioned that the in–house staff was the basis for the formation of the establishment of the Reliance strengths. That was true to the extent that scientists and engineers in house included those involved running outside contracts, technical managers of outside contracts. The R&D funding that went to outside contracts through that channel was also included in the accounting of who had the lead laboratory status. It wasn't just how many true in–house S&T scientists were available, but also how much funding they could leverage through contracts.

JOHN VIG (ARL): Any questions from the audience?

HAROLD CHADSEY (USNO): You're talking about having a joint thing where one lab knows what another lab is doing. The Naval Observatory is not that large a lab in comparison to many others and to the entire DoD community. We have problems enough figuring out what the person in the other building is doing. If they have a program that they had already written and everything set up for, and we could use that program, sometimes it's quite by accident that we find out about it. How do you propose and implement at what time a communication between one lab and another lab happens, and prevent the idea of "empire building" and somebody saying "Well I'm not going to give you that information because it will tear away from my empire?"

JOHN VIG (ARL): You have no choice. Even long before Reliance was created, there was another panel called the AGED, the Advisory Group Electron Devices. Before we could initiate

any contractual programs, if not in-house, we had to do was called an "AGED write-up;" we had to describe in just two or three pages as to what the program goals were; what the rationale was for the program; what the projected funding levels are; and who's going to be in charge of running the program; and who are the probable contractors who will bid on the program. This went to the AGED panel, which consisted of outside DoD, high-level executives, like vice-presidents of corporations, senior professors at universities and such. The AGED panel would look at these programs and look at the programs submitted by the Air Force and the Navy, and made sure that there was no duplication of effort; and also it was distributed to all the laboratories to make sure everybody knew what the other guy was planning.

So there was a formal mechanism to make sure that at least contractual programs were pretty well coordinated. Now this Reliance was to take the next step, and that is to make sure that all programs, whether they are contractual or in-house, were well coordinated; and not only coordinated, but actually performed jointly. So whereas before, if I decide I wanted to do a program on a very low power compensated oscillator, we would create a program; and write up a work statement; and then do an AGED write-up; and then it would get coordinated; and then it would be sent to the Navy and the Air Force to make sure they knew what the Army was doing.

Now, even before we do anything, we are supposed to contact our counterparts in the Navy and Air Force and jointly decide what should be done, jointly write the work statement, jointly do everything in the process of creating this contractual program. That's the theory anyway. Has it happened that way in reality? Not really. In large part, because we just simply don't have much money for contracts. So since the Reliance was created, we haven't had many contracts.

RONALD BEARD (NRL): I think communication is a problem, though, even in these joint efforts. Certainly in large efforts like this, it's very difficult – as he pointed out, it's difficult to communicate across the lab. It's even more difficult to communicate from laboratory to laboratory, especially on a programmatic level. That is a significant problem.

FREDERICK BETZ (NRL): Yet, that was one of the fundamental purposes of forming the Reliance panel in the area of astrometry. In astrometry, there was a single service identified, and perhaps it's time to readdress the technology centers of excellence across all the services if there's going to be a reevaluation and the realignment of the technology panels, so that USNO could participate with the Army and the Air Force personnel who are doing work in frequency.

JOHN VIG (ARL): In our technology area, there is an additional coordination mechanism, and that's the PTTI coordination meetings that we have every year at the USNO. Under Dr. Winkler's leadership, all the government organizations that are involved in PTTI technology get together and share information.

GERNOT M. WINKLER (USNO): I just want to correct one impression that exists persistently, and that is that the USNO is not a laboratory. The distinction is very important. We are part of an operational part of the Navy. This is not under the research and development organization which, for instance, is, of course, the case with NRL, which is under the Chief of Naval Research. Similarly in the other services.

Therefore, we are not a competitor in any way. We are a user of results of research and

development. That is the function of the USNO. Independently and separately from that, of course, is our role as the PTTI managers for DoD. In that regard, we have a coordination function, as you just mentioned, Dr. Vig.

I just wanted to keep that separate as much as we can, because otherwise, if things are that way, you always get into wrong conclusions. So we are not a laboratory, and that distinction is very important.

FREDERICK BETZ (NRL): I just had an opportunity to look at the document that came out in September of this year called "The Defense Technology Plan." I couldn't find anything in here, at least in the major headings, that dealt with precision timing or frequency. It may be buried deep down somewhere in one of the panels or subpanels, but it certainly isn't addressed as part of the a technology S&T effort at the Director of Defense Research and Engineering level.

JOHN VIG (ARL): That is because that document doesn't go down to the sub–subpanel level. That's where frequency control sits. There is an electronic devices panel under which there are a number of subpanels, one of which is RF components. Frequency control is a sub–subpanel in RF components technology. I think that only goes down to RF components and not to the sub–subpanel level.

We are a very small part of the total DoD electronic devices effort. In solid–state technology, when you look at the funding charts, we are a little blip; solid–state technology is probably 50 times as large in funding levels.

RONALD BEARD (NRL): Well, I'm not so sure that we should be a major heading under "Science and Technology" per se. But on the other hand, we could be part of the sub–sub–sub–sub–subpanel that's absolutely totally forgotten.

That's something I think we shouldn't allow to happen; because, this technology is taken so much for granted that people just assume you know time; I mean, people are familiar with time, they look at their watches everyday so that they can be at work on time. But it's not really viewed as a technology; and from that perspective, it just can be "subbed" into oblivion. I think that's the issue that I would like to bring forth, so that people can be aware of this when they're communicating with developers and people who are doing contracts and developing systems and those sorts of things.

You just can't take time for granted. It has to be generated, it has to be nurtured, and it has to be taken care of.

JOHN VIG (ARL): We also have an image problem. I have heard frequency control and clock technology it referred to as "that old technology."

JOE WHITE (NRL): Let me encourage a little bit of speculation for a minute. You all have talked about, number one, that within the time and frequency community we have done a fair amount of coordination; there's a mechanism to it. I think there has always been kind of a division of labor, particularly between our group and John's group, in terms of who did what. You generally work in the crystal and the portable technology, we tend to do work in the space area.

I think also, as Fred has pointed out, a lot of these meetings at a higher level don't really reflect that kind of a coordination going on, not necessarily in our area, but in general. Do you think we're in some danger, either at the DoD level or even at the service level, of somebody deciding to merge functions and solve our problems for us? Even though we may not have any problems, are we going to be swept into laboratory mergers or whatever? Anybody have a feeling about that?

JOHN VIG (ARL): Some of the cynics think that the whole idea of JDL Reliance was to prevent what is called the "purple–ization of DoD laboratories." "Purple" means forming a single – you know, the Army is green, the Air Force is blue and the Navy is, I guess, white. So, "purple" is a term that people have been using as a merging of the three services' efforts.

I believe that even now there are serious proposals being considered for merging the three organizations and creating a single DoD laboratory structure. Perhaps Helmut Hellwig is in a position to address that question.

HELMUT HELLWIG (AF OFFICE OF SCIENTIFIC RESEARCH): Let me comment on a couple of these questions.

The issue of the old Reliance and the incubating defense investment strategy, which I think is the current best word and the official word – I think it's on your document too – the issue is not whether or not you work with the other lab; the issue is that you don't have enough money to do what you used to do. So you are questioning where do you put the money; several dimensions, where do you put it and topics. So the question for time and frequency is not USNO versus NRL versus whatever goes on in the Air Force. By the way, something still goes on in the Air Force, in the extramural program; we're on a very solid 6.1 program.

The issue is: Should there be time and frequency in any DoD activity? Should Ron Beard go out of existence? That is the issue. Why could he go out of existence? Don't get me wrong here, there's no proposal, to the best of my knowledge, of that nature on the table. So I'm just giving you a fictitious view of the world. But it is the kind of thinking I want to project. Why couldn't he go out of the existence in the thinking of defense managers? Because of NIST and Hewlett Packard? That's why.

I think the challenge for the time and frequency DoD community is to prove that they add something significant to defense, in view of the ongoing academic and commercial activities. The issue has graduated very much from being an issue of "Are you working together?", yes, no, to "Why do you exist in view of other efforts?" "Should we use the money you are earning for things where it is more needed?" That is the issue, and it will be with us for the rest of the century.

PHILLIP E. TALLEY (RETIRED FROM AEROSPACE CORPORATION): Along the line of this discussion, I think that one shortcoming is that potential contractors for various large systems don't really know where within the government to go for advice for time and frequency. I've been inclined to recommend going to see Dr. Winkler as a source of what's available, and possibly recommendations of how to approach the time and frequency problems. But people don't seem to appreciate that there is help out there. I think the integration of labs, or whatever happens, needs to address this and make it known to the various industrial

contractors that service is available; and we need to know this in order to direct the efforts in whatever laboratory activities are going on, but will satisfy the needs for the future contractors.

JOHN VIG (ARL): We spend a considerable portion of our time answering questions over the telephone and having visitors come to us and ask us about oscillators. That is an important function that we perform. But that's not what sells programs when we go for our annual reviews. To say that we have advised a corporation or have answered questions from industry does not buy us much. If we have developed a new gizmo that we can demonstrate increases battery life in a tactical radio, because the power consumption of this oscillator is ten times lower than before, that's the kind of thing that sells programs. Or, if you can make tiny little atomic clocks versus the 19 inch rack atomic clocks, and you can explain what the significance is in future military systems, that can sell programs.

But you are right. That's an important function that government laboratories can and do serve. But that's sort of a side issue.

EDWARD POWERS (NRL): One final question here. Speaking of the Aerospace Corporation, other government laboratories, are they following this anywhere?

JOHN VIG (ARL): Not that I know of, no.

RONALD BEARD (NRL): One final quick comment. I think Helmut made some very good points, specifically that my group wasn't targeted for extinction. But I think that is the key issue. Since the resources and funding is going to be much more limited than it has been in the past, what are the technologies doing for you, compared to what is available? And, does additional research need to be done? In the additional research, where can you get the best available? That is the key issue.

JOHN VIG (ARL): We have an image problem. I think when there are annual reviews, and people get up and talk about these micro–electromechanical devices, tiny, tiny microscopic motors and actuators and pumps and various other devices, those are considered to be the sexy technologies. It's hard to compete with that when you are talking about a new generation of clocks, for example.

RONALD BEARD (NRL): The "glitzy" technologies.

Ed Powers (NSR): I would to thank the panel and the audience for their participation in this discussion.